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*SPECTROSCOPY OF ATOMS AND MOLECULES*

# A SINGLE ATOM AS A QUANTUM INTERFEROMETER

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The possibilities of using a single atom in a quantum superpositional state of an angular momentum as a quantum interferometer are demonstrated. A feasible realization of experiments with an atom similar to those performed with single- and double-particle interferometers on photons in order to test the foundations of quantum mechanics is discussed. The changes in the visibility of interference patterns in accordance with the information once made available about the atomic state are analyzed. The possibility of quantum "eraser" type experiments with atoms, earlier realized with photons and neutrons, is discussed.

The analysis of advantages and disadvantages of the use of an atom as quantum interferometer in comparison with single- and double-particle interferometers with photons is presented. The difference between a single particle superpositional state with components separated in linear coordinates and in angular momentum coordinates is briefly touched upon.

**Keywords:** quantum interference, superpositional state, particle interferometer

## I. INTRODUCTION

The particle analog of Thomas Young's classic double-slit interference experiment still plays a very important role in contemporary physics. A practical realization of such an interferometer with electrons and protons is hampered by their strong electromagnetic interaction with the environment, but neutron interferometers operate in many laboratories [1]. In the last decade, Young's optical experiment was directly repeated with neutrons using a mechanical double slit of dimensions of 20 $\mu$m and neutrons with the de Broglie wave length $\lambda_D$=15÷30 Å [2].

Despite the fact that the interference of the de Broglie waves of neutral atoms and even of small molecules was demonstrated by Otto Stern as early as in 1929 [3], atom interferometers — challenged due to a small de Broglie wave length (typically 1 Å for thermal atomic beams)—became a powerful tool to measure the acceleration resulting from gravitation, rotations, and the photon recoil of an atom [4, 5] only very recently .

A special type of particle interferometers — *single particle interferometers* — attracts especially the attention of those who try to check the foundations of quantum mechanics. These are interferometers with only one particle passing through the device at a time. Such interferometers and their close counterparts — *two-particle interferometers* — made it possible in the past years to demonstrate that the Bell inequality [6] is violated (in accordance with the laws of quantum mechanics) in the correlation measurements between spin states of protons [7], the states of photon polarization [8, 9], and the phase and momentum of photons [10]. All these experiments helped to examine the nonlocality of quantum mechanics.

These one- and two-particle interferometers allowed measurements of the tunneling time of a photon [11]. *Non-interactive measurements* were also demonstrated to be possible in quantum mechanics [12]. By these devices the changes in the visibility of the interference pattern in accordance with the information available about the state of particles in the interferometer were demonstrated [13]. Experiments showing the possibility to "erase" information once made available about the state of a photon were also performed [14]. In the heart of quantum interference experiments there lay one-particle and two-particle superposition states.

So far, all but a few [2, 7] technically very complicated experiments intended to check the foundations of quantum mechanics and the one-particle superposition principle were performed on photons.

In this paper, it is demonstrated that there exists another possibility to carry out such experiments in a very simple way by using a *single atom* as quantum interferometer allowing us to realize the one-particle superposition state.

In this paper, it is also tried to bring together ideas about tests of foundations of quantum mechanics and the experience of atomic physicists who have been investigating the effect of the interference of atomic states during the last 30 years [15]. To make it easy to understand the main ideas, a very simple model is used. However, this simple model of a two-level atom with zero total electron spin — with slow decay and without hyperfine structure — allows us to demonstrate all the advantages that atomic physics experiments can provide to analyze the foundations of quantum mechanics.

It seems that those experimental possibilities atomic physics can offer to tackle long lasting quantum mechanical puzzles are not yet fully understood and exploited, although the interference of atomic states is successfully used to solve specific problems of atomic and molecular physics [15, 16].

## II. ANALOGY BETWEEN MACH–ZEHNDER TYPE PARTICLE INTERFEROMETER AND INTERFERENCE OF ATOMIC STATES

### *A. SINGLE ATOM INTERFERENCE*

In the first proposal of the experimental realization of a quantum mechanical interaction-free measurement, the Mach–Zehnder type particle interferometer as a device to make such measurements possible was analyzed [17]. One of the key points for the use of this interferometer for tests of the foundations of quantum mechanics is that when a single photon hits the first beam splitter BS1 (see Fig. 1*a*) its wave function can be written as [17]

$$|photon\rangle = 2^{-1/2}|1\rangle + i2^{-1/2}|2\rangle, \tag{1}$$

where $|1\rangle$ represents the state of the photon transmitted through the beam splitter, but $|2\rangle$ a state of the reflected photon. Of course, for a more detailed description of a photon one needs all the power of the mathematical apparatus of quantum optics, but even this simplified form (1) allows us to demonstrate the key moments of the problem. A very good analysis of quantum optics approaches to a description of one- and two-photon interferometers was given in a recent review [18]. There was also shown that the phenomenological description of the Mach–Zehnder interferometer is identical to that of the Michelson interferometer. It means that a single atom interferometer can be compared with the Michelson interferometer equally well.

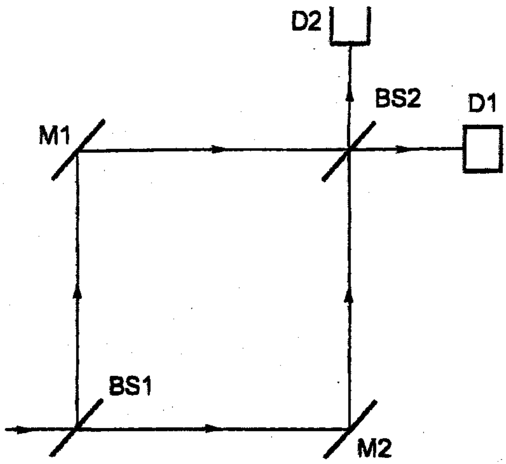


*Fig. 1.* Mach–Zehnder interferometer

As a result of the action of a beam splitter, the photon appears in a one-particle superposition state consisting of two partial components $|1\rangle$ and $|2\rangle$. For a half transparent beam splitter the respective amplitudes of the components are $2^{-1/2}$. From the law of conservation of energy it follows immediately that the transformation matrix that characterizes the beam splitter must be unitary, and, consequently, the relative phase of the reflected and the transmitted beams is exp $(i\pi/2)$ = i.

A very similar one-particle superposition state can be achieved when an atom absorbs light of an appropriate polarization. Let us consider an atom with a ground state possessing an angular momentum represented by a quantum number $j_g = 0$ and an excited state with an angular momentum represented by a quantum number $j_e = 1$. The ground state consists of one magnetic sublevel with the magnetic quantum number $m_{j_g} = 0$, and the excited state of three magnetic sublevels $m_{j_e} = -1, 0, +1$, see Fig. 2*a*.

Suppose that such an atom absorbs the linearly polarized light in a geometry as shown in Fig. 2*b*. The unit vector along the direction of the polarization $\mathbf{E}_e$ of the exciting light can be represented by the following components $E_e^q$ in a cyclic system of coordinates [16]

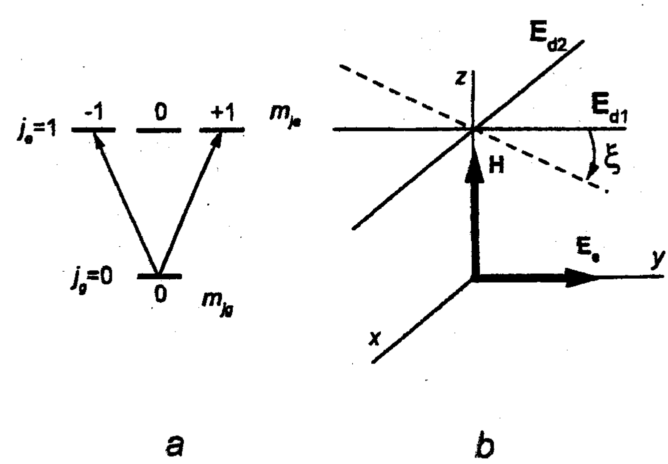


*Fig. 2.* Atom as a quantum interferometer;
*a* — energy level scheme,
*b* — geometry of excitation and observation

$$E_e^{+1} = -2^{-1/2}(E_x - iE_y) = i2^{-1/2},$$
$$E_e^0 = E_z = 0, \tag{2}$$
$$E_e^{-1} = 2^{-1/2}(E_x + iE_y) = i2^{-1/2}.$$

After absorption of light with the given polarization, the atom in an excited state will appear in a single particle superposition state

$$|atom\rangle = \sum_{m_{j_e}} c_{m_{j_e}} |m_{j_e}\rangle \exp(-i\varepsilon_{m_{j_e}} t/\hbar) =$$
$$= -i2^{-1/2} \exp(-i\varepsilon_{-1} t/\hbar)\, |-1\rangle_\varepsilon - i2^{-1/2} \exp(-i\varepsilon_{+1} t/\hbar)\, |+1\rangle_\varepsilon, \tag{3}$$

where the amplitude of the partial components $|-1\rangle_\varepsilon$ and $|+1\rangle_\varepsilon$ of the total wave function can be calculated according to [16] as

$$c_{m_{j_e}} = \langle m_{j_e} | E_e^* \hat{d} | m_{j_g} \rangle =$$
$$= \sum_{m_{j_g}, q} (E_e^q)^* C_{j_g m_{j_g} 1q}^{j_e m_{j_e}} (2j_e + 1)^{-1/2} (j_e || \hat{d} || j_g), \tag{4}$$

where $\hat{d}$ is an operator of the transition dipole moment, $C_{j_g m_{j_g} 1q}^{j_e m_{j_e}}$ — the Clebsch–Gordan coefficient [19] — and, finally, $(j_e || \hat{d} || j_g)$ is a reduced matrix element independent of $m_{j_e}$ and $m_{j_g}$. It plays no role in further discussions and is omitted for the sake of shortness of notations, as well as a factor $(2j_e + 1)^{-1/2}$ in (3) and further on. The partial wave functions in this case are angular momentum states representing different angular momentum spatial orientation with respect to the quantization axis $z$.

From Eq. (3), we see that the state of an atom after the absorption consists of two components, namely $|-1\rangle_\varepsilon$ and $|+1\rangle_\varepsilon$ in the same way as the state of a photon in the Mach–Zehnder interferometer after the first beam splitter. The amplitudes of both components of the wave function are again equal to $2^{-1/2}$, and their relative phase depends on the phase factors $-i \exp(-i\varepsilon_{m_{j_e}} t/\hbar)$. This relative phase can be a time-dependent quantity if energies of magnetic sublevels are not equal, i.e., $\varepsilon_{-1} \neq \varepsilon_{+1}$. The latter situation can be exploited in interference experiments, as will be demonstrated later.

To observe the interference of two coherent partial states of a particle in a Mach–Zehnder type interferometer, mirrors M1 and M2 are used (see Fig. 1*a*) to join two possible trajectories of the photon in one point on the second beam splitter BS2. If both passes of the photon to the second beam splitter BS2 are of equal optical path length, the partial waves on the detector D1 will arrive in phase (one reflection in a beam splitter for each wave), the constructive interference will happen, and the detector will click with certainty. On the contrary, partial waves will be with opposite phases on the detector D2 (two reflections in a beam splitter for the first and no reflections for the second wave), the destructive interference will happen and the detector will have zero probability to detect the photon.

How can the interference of partial wave functions be observed in the case of one atom? For this, we must detect light with a detector sensitive to a certain polarization, when after the absorption the atom decays to the initial ground state. If in the detection we choose the linear polarization of the analyzer with direction of polarization $\mathbf{E}_d$ parallel to the $\mathbf{E}_e$-vector of excitation, we have the following cyclic components of $\mathbf{E}_d$ :

$$
\begin{aligned}
&E_{d1}^{+1} = i2^{-1/2},\\
&E_{d1}^{0} = 0, \qquad\qquad (5)\\
&E_{d1}^{-1} = i2^{-1/2}.
\end{aligned}
$$

As far as $E_{d1}^{-1}$ and $E_{d1}^{+1}$ have equal phases and if the energies of both atomic sublevels $\varepsilon_{-1}$ and $\varepsilon_{+1}$ are equal (which is always the case if no external fields are applied), this means that both partial states of the atom are in phase when their interference is detected and we can expect constructive interference. The probability to detect a fluorescence with such polarization is maximal. This orientation of the analyzer in a detector corresponds to the detector D1 in the Mach–Zehnder interferometer.

On the contrary, if we set the vector $\mathbf{E}_d$ of the analyzer in the detector perpendicular to the vector of excitation, then $\mathbf{E}_d$ will have the components:

$$
\begin{aligned}
&E_{d2}^{+1} = -2^{-1/2},\\
&E_{d2}^{0} = 0, \qquad\qquad (6)\\
&E_{d2}^{-1} = 2^{-1/2}.
\end{aligned}
$$

We see that $E_{d2}^{-1}$ and $E_{d2}^{+1}$ have opposite phases and we can expect a destructive interference of partial atomic wave functions and zero probability to detect fluorescence in this detector. This polarization of the observation corresponds to the detector D2 in Mach–Zehnder interferometer.

To make sure that this qualitative analysis is correct, let us perform an exact calculation of the probability to detect fluorescence emitted by an atom for arbitrary orientation of the analyzer in the detector. For this, a *semiclassical* approach will be used. This means that we consider the atom in a quantum manner and the light in a classical way. It is assumed in this approach that the probability to detect the photon emitted by the atom is proportional to the square of the light field averaged over the detection volume. For this description, we use the quantum mechanics density matrix $f_{mm'}$ [20], which, in a most natural way, accounts for amplitudes and relative phases of all partial components of the wave function of an atom. In our case, the density matrix of an excited state of an atom can be expressed as [16]

$$\dot{f}_{m_{j_e} m'_{j_e}} = \Gamma_p \langle m_{j_e} | E_e^* \hat{d} | m_{j_g} \rangle \langle m'_{j_e} | E_e^* \hat{d} | m_{j_g} \rangle^* -$$

$$- i[(\varepsilon_{m_{j_e}} - \varepsilon_{m_{j_e}'})/\hbar] f_{m_{j_e} m_{j_e}'} =$$

$$= \Gamma_p \frac{|(j_e||\hat{d}||j_g)|^2}{(2j_e+1)} \sum_{m_{j_g} q_1 q_2} (E_e^{q_1})^* E_e^{q_2} C_{j_g m_{j_g} 1 q_1}^{j_e m_{j_e}} C_{j_g m_{j_g} 1 q_2}^{j_e m_{j_e}'} -$$

$$- i\omega_{m_{j_e} m_{j_e}'} f_{m_{j_e} m_{j_e}'}, \tag{7}$$

where $\Gamma_p$ is an absorption probability. Knowledge of the density matrix of the excited state of an atom allows us to calculate the probability to emit light of a definite polarization $\mathbf{E}_d$. In our example it is [16]

$$P = \sum_{m_{j_e} m_{j_e}'} \langle m_{j_g} | E_d^* \hat{d} | m_{j_e} \rangle \langle m_{j_g} | E_d^* \hat{d} | m_{j_e}' \rangle^* f_{m_{j_e} m_{j_e}'} =$$

$$= \sum_{m_{j_e} m_{j_e}'} \frac{|(j_e||\hat{d}||j_g)|^2}{(2j_e+1)} \times$$

$$\times \sum_{m_{j_g} q_1 q_2} (-1)^{q_1+q_2} (E_d^{-q_1})^* E_d^{-q_2} C_{j_g m_{j_g} 1 q_1}^{j_e m_{j_e}} C_{j_g m_{j_g} 1 q_2}^{j_e m_{j_e}'} f_{m_{j_e} m_{j_e}'}. \tag{8}$$

If we calculate this probability $P$ as dependent on the angle $\xi$, see Fig. 2*b*, between $\mathbf{E}_e$ and $\mathbf{E}_d$, we obtain

$$P = \frac{1}{2}(1 + \cos 2\xi), \tag{9}$$

which is in full agreement with our qualitative analysis performed above.

### B. *MEASUREMENTS WITH A SINGLE ATOM INTERFEROMETER*

Despite the fact that a possibility to examine experimentally the interference of an atomic state is interesting in itself, to make use of an interferometer we need a possibility to alter the channels. In the Mach–Zehnder interferometer it can be done by introducing the phase shift by changing the optical path length of the channels, or changing the amplitude of one of the partial components of the wave function by altering the channels' transparency with some additional elements. In doing so we make these channels unequivalent. Can it also be done in the case of an atom? Of course, it can be done, but not in the same way as in the case of the Mach–Zehnder interferometer, although either phase or amplitude of the partial wave functions of an atom can be altered.

Let us consider an atom in an external magnetic field that is directed along the $z$-axis, see Fig. 2*b*. This field locally breaks the anisotropy of the space by setting a singled-out direction. It means that angular momentum states differing in spatial orientation will no longer be equivalent. In this field, atomic sublevels will gain additional energy in accordance with the well-known Zeeman effect formula. If we consider an atom with the total spin moment $S=0$, we have

$$\varepsilon_{m_{j_e}} = \mu_B H m_{j_e}, \tag{10}$$

where $H$ is the magnetic field strength, $\mu_B$ — Bohr magneton. As a result, in the magnetic field, phase difference between partial components of the wave function (3) will be changing in time. Obviously, we can also expect the probability to detect light from such an atom with either of detectors to be changing in time. The results of exact calculations according to (7) and (8) yield

$$P = \frac{1}{2}[1 + \cos(\omega t - 2\xi)], \tag{11}$$

where $\omega = (\varepsilon_{+1} - \varepsilon_{-1})/\hbar = 2\mu_B H/\hbar$ . This formula shows that if we are absolutely unaware from which state — $|+1\rangle_e$ or $|-1\rangle_e$ — the atom radiates (i.e., which pass it takes from the ground state to the excited state and back), we will have the 100% modulation depth of the probability to detect fluorescence.

## 1. Visibility of an interference pattern

Can this modulation depth be changed if we obtain information about the substate from which the atom decays? The answer is yes. The difference of two possible decay channels $|+1\rangle_e \to |0\rangle_g$ and $|-1\rangle_e \to |0\rangle_g$ is that in the first case the atom in the positive direction of the $z$-axis radiates lefthand circular polarized light, while in the second case righthand circular polarized one [16]. All we need to determine from which substate the atom decays is to detect the circularity of the emitted light. Let us assume that the analyzer in front of our detector filters the righthand polarized light with probability $|a^d_{-1}|^2$ and the lefthand polarized light with probability $|a^d_{+1}|^2$. From an experimental viewpoint, this means that the detector is sensitive to the light with a certain ellipticity. Such a detector can easily be realized by means of a quarter wave plate with a subsequent appropriately oriented linear polarizer [21]. Assuming the normalization $|a^d_{-1}|^2 + |a^d_{+1}|^2 = 1$, the cyclic components of $\mathbf{E}_d$ can be written as [16]

$$\begin{aligned} E_d^{-1} &= a^d_{-1}, \\ E_d^0 &= 0, \\ E_d^{+1} &= a^d_{+1}. \end{aligned} \tag{12}$$

For simplicity and without losing the generality of the obtained results, we can assume that $a^d_i$ are real numbers [16]. Then, according to our procedure, the probability to detect fluorescence from an atom in a magnetic field can be calculated as

$$P = \frac{1}{2}(1 + 2a^d_{+1} a^d_{-1} \cos \omega t). \tag{13}$$

It means that we can predict the 100% modulation depth or the 100% visibility of interference if our detector transmits lefthand and righthand circular polarized light with equal probability, and zero visibility or modulation depth if we detect a definite circularly polarized light with a certainty, i.e., $|a^d_{-1}|^2 = 1$ and $|a^d_{+1}|^2 = 0$ or $|a^d_{-1}|^2 = 0$ and $|a^d_{+1}|^2 = 1$. In the intermediate cases, the modulation depth or the visibility of interference must vary according to the extent the information about the decay channel can be obtained with our detector. A similar experiment was carried out with photons, demonstrating in a two-particle interferometer how the information obtained about the path of particles changes the visibility in an interference pattern in accordance with quantum mechanical predictions [13, 22].

In a similar way as by means of an analyzer we can set a detector such that every time the detector clicks we know that with probability $|a^d_{+1}|^2$ a lefthand circular polarized light is emitted, and with probability $1 - |a^d_{+1}|^2$ a righthand polarized light is emitted; we can choose the polarization of excitation such that we know that with probability $|a^e_{+1}|^2$ an atom is excited to the substate $|+1\rangle_e$, and with probability $1 - |a^e_{+1}|^2$ to the substate $|-1\rangle_e$. The same as for the detection, this will decrease the visibility of an interference pattern in relation to the available information about the substate being excited.

## 2. Quantum "eraser" experiment with an atom

Combining the appropriately organized excitation of an atom by elliptically polarized light with the observation by means of a detector sensitive to elliptically polarized light of different ellipticity, one can check another effect known from experiments with photons [14] and neutrons [23], namely, the possibility to "erase" information once made available about quantum states.

Let us assume there is an excitation with elliptically polarized light, such that

$$E_e^{-1} = a^e_{-1},$$
$$E_e^{0} = 0, \quad (14)$$
$$E_e^{+1} = a^e_{+1},$$

where $a^e_i$ are chosen to be real gain. The created excited state of the atom in this case will be characterized by a wave function

$$|atom\rangle = a^e_{-1} \exp(-i\varepsilon_{-1} t/\hbar)|-1\rangle_e + a^e_{+1} \exp(-i\varepsilon_{+1} t/\hbar)|+1\rangle_e \quad (15)$$

and the visibility of the interference pattern at the linearly polarized observation can be determined from the probability to detect linear polarized light

$$P = \frac{1}{2}[1 + 2a^e_{-1} a^e_{+1} \cos(\omega t - 2\xi)]. \quad (16)$$

If we know which atomic sublevel is preferably excited (i.e., $a^e_{-1} \neq a^e_{+1}$ ), then the visibility of the interference pattern will be decreased.

However, this visibility can be restored if we choose the polarization of an analyzer in front of the detector opposite to the polarization of the excitation such that the information once made available in the process of excitation will be lost afterwards, or, more precisely, will not be used in the process of detection. It means we must set

$$\begin{aligned} &E_d^{-1} = a_{-1}^d = E_e^{+1} = a_{+1}^e, \\ &E_d^0 = E_e^0 = 0, \\ &E_d^{+1} = a_{+1}^d = E_e^{-1} = a_{-1}^e. \end{aligned} \tag{17}$$

Such setting means that a higher probability to excite a definite atomic substate will be compensated by a lower sensibility of the detector to the decay of an atom from this substate and vice versa. As a result, when the detector clicks we have again the equal probability that our atom–quantum interferometer has made a pass $|0\rangle_g \to |+1\rangle_e \to |0\rangle_g$ or $|0\rangle_g \to |-1\rangle_e \to |0\rangle_g$, which means that the information about preference to excite a specific atomic state can be erased by an appropriately organized observation. Applying quantitatively the method used above, we can write the probability of detecting fluorescence

$$P = 2a^2 (1 - a^2)(1 + \cos \omega t), \tag{18}$$

where $a = a_{+1}^e = a_{-1}^d$. The expression obtained is in full agreement with the predictions made in our qualitative discussion above.

## III. DISCUSSION AND CONCLUDING REMARKS

In the previous Section, yet unexploited possibilities were shown how the use of a single atom as quantum interferometer offers verification of the foundations of quantum mechanics.

Can we find a real atom suitable to perform the experiments proposed in this paper? There may be several candidates, but the $^{40}Ca$ atom is probably the best one. This atom has a $(4s^2)\ ^1S_0$ ground state and a $(4s4p^1)\ ^1P_1$ excited state. The transition wavelength is 4227 Å, which is in the visible region of the spectrum. This atom has no hyperfine structure, which could complicate interpretation of the results. The lifetime $\tau$ of the excited state is a few ns. Ca atoms have already been used several times to produce photon pairs for optical experiments testing the foundations of quantum mechanics [8, 9, 24], but, of course, Ca is not the only possible candidate.

Interference experiments with single atoms have remarkable advantages in comparison with single-particle interferometers. One can use simultaneously many identical atom-interferometers. Experiments can be carried out in thermal cells or in atomic beams. An ensemble of atoms can be irradiated with rather intense laser light. At these conditions, every atom at a time will be able to absorb only one photon, but if the laser pulse is short enough in comparison with the atom lifetime $\tau$ and frequency $\omega$, then the interference beats from all atoms will be synchronized by excitation. As a result, we observe an intense interference signal that can be detected with conventional technique. We need not collect data for many hours to obtain a reasonable signal–to–noise ratio, as it sometimes happens with traditional single-particle interferometers, see [11].

An argument can be put forward that the interference of atomic states in the analyzed sense is less interesting and less striking than interference of photon states in single- and two-particle interferometers because coherent atomic states contrary to photon states in these interferometers are not spatially separated.

This is only partially true because coherent partial components of atomic wave function in the discussed experiments differ in the spatial *orientation* of angular momentum. It seems to be equally important to examine what it means and how it can be understood that a photon is simultaneously in several places in space, or what it means that an atom has simultaneously several (opposite $|-1\rangle_e$ and $|+1\rangle_e$ in the discussed examples) orientations of the angular momentum in space.

Finally, in Stern–Gerlach type setups it is possible in general to have coherently excited atomic states that differ in the angular momentum orientation and, at the same time, are separated in space.

Another objection that can be made is that in proposed experiments with an atom we actually observe the same single-photon quantum interference, only the photon is prepared in a peculiar way. This argument can be dismissed because in the analysis of the proposed experiments we used a semiclassical approach in which only the atom is considered quantum mechanically, while the light — classically. In this case, light serves only as the information carrier allowing one to obtain the information about interference of atomic states.

If atoms are also treated classically as ordinary dipole oscillators, instead of Eq. (11) we will have [16]

$$P = \frac{1}{2}\left[1 + \frac{1}{7}\cos(\omega t - 2\xi)\right], \tag{19}$$

where, instead of interference visibility 1 in case of the analyzed atomic transition, now we have visibility only 1/7 . This difference can serve as a quantitative measure of the nonclassicality of the described interference. In classical approach, the physical meaning of $\omega$ is the frequency of precession of an oscillator in an external magnetic field. Difference between amplitudes 1 in Eq. (11) and 1/7 in Eq. (19) serves as a measure of "nonclassicality" of the quantum interference. This nonclassicality is a one–particle interference counterpart of Bell's inequality [6] derived to characterize the difference of observable results in quantum and classical approaches in case of two–particle interference.

Actually, the effect of atomic state interference has already been known to atomic physicists [15], but it was never applied in experiments to verify the foundations of quantum mechanics. In atomic physics, this effect—known as "quantum beats"— is used to measure such atomic properties as magnetic moment, hyperfine splitting, etc.

The use of a single atom as quantum interferometer is not restricted to the $0 \longrightarrow 1 \longrightarrow 0$ transition only. Practically every transition is suitable, but for higher angular momentum values the number of coherently excited substates will be larger. It will make the description more complicated only technically, since the theory itself is well-developed [16, 20]. Exploitation of states with larger $j$ values of angular momentum quantum number can also bring some advantages. First, at nonlinear light absorption we can excite many substates (e.g., partial wave functions) coherently [16, 25]. It will resemble multi-particle interference, or interference gratings in optics. As we know, in this case the interference peaks are much narrower and sharper. This fact can prove advantageous in precision measurements. Second, in special conditions (which are analyzed in detail in [26]), even if we have but pairs of coherently excited substates (several of them simultaneously in one atom or molecule) we can again expect very sharp and narrow resonances in the obtained interference pattern. And, finally, by coherently excited particles with large angular momentum values, say $j \sim 100$ (usually in the case of molecules), we still have a quantum interference, but these angular momentum states are almost classical and can be described at the same time quantum–mechanically, using quantum density matrix formalism, and classically, using continuous probability density of the spatial orientation of angular momentum j. It means that in such systems we can address another striking problem — namely, how the quantum interference will look in a transition to a classical limit. As is shown in [16, 25], the general answer is that it will survive, but this question deserves special attention and further investigation.


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## ATSEVIŠĶS ATOMS KĀ KVANTU INTERFEROMETRS

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Anotācija

Rakstā ir parādīta iespēja atomu leņķiskā momenta kvantu superpozīcijas stāvoklī izmantot kā kvantu interferometru. Tiek apspriesta tāda interferences eksperimenta ar atomiem iespējamā realizācija, kas būtu līdzīgs viendaļiņas un divdaļiņu eksperimentiem, kuri līdz šim ir tikuši realizēti ar fotoniem. Ir analizētas interferences ainas redzamības izmaiņas atkarībā no pieejamās informācijas par atoma stāvokli. Rakstā ir apspriesta iespējamība izveidot "kvantu dzēšgumijas" tipa eksperimentu ar atomiem. Šāda tipa eksperimenti jau ir realizēti izmantojot fotonus.

Tiek analizētas priekšrocības un trūkumi, kas piemīt kvantu interferences eksperimentu realizācijai ar atomiem salīdzinot ar līdzīga tipa viendaļiņas un divdaļiņu eksperimentiem, kas ir realizēti izmantojot fotonus. Ir apspriesta starpība starp viendaļiņu superpozicionālo stāvokli, kad komponentes ir telpiski atdalītas un situāciju, kad superpozicionālā stāvoklī atrodas leņķiskā momenta komponentes.

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