Time reversal noninvariance in quantum physics.

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A number of direct and indirect experimental proofs of the nonequivalence of forward and reversed processes in quantum physics were discussed in e-print viXra:1804.0359. Here we have added a discussion of three else physical phenomena: the so-called optical precursor, entangled two-photon absorption and the Hong-Ou-Mandel effect.

Physics is essentially a simple science.
The main problem in it is to understand
which symbol means what.
V.A. Fock

Introduction.

Mathematics plays an important role in physics. Physical laws are often expressed in mathematical form. However, for many years a strange situation has developed, when the mathematical description of physical phenomena became more important than their physical explanation.

The most striking example here is quantum mechanics. It describes the experimental results very well, but the long-standing heated discussion about its physical interpretation seems endless.

A similar situation is observed in optics, nonlinear optics. Here, a lot of physical phenomena usually have a good mathematical description. However, physical explanations of the nature of the phenomena are either absent at all, or they are helpless. In general, the situation in quantum physics is still best characterized by a well-known expression: "Shut up and calculate" [1].

We believe that the exit from this deadlock lies on the way of understanding of symmetry of physical laws. In particular, in the symmetry of time reversal. Theorists, probably, well understand this problem [2-4]. But it must be solved in experimental way.

Other strange situation is that the fact of violation of CP and T invariance has been long discovered in the field of high energy physics [3, 5]. The scientific community has recognized it. However, in the field of low-energy physics (optics, conventional quantum physics) it is still widely believed, that the laws of physics are symmetrical in time.

Many years physicists try to find microscopic signs of violation of T-invariance. And they make it by a very exotic way: trying to find the so-called electric dipole moment [6]. It is surprising that nobody now tries to compare directly properties of forward and reversed processes in optics.

Although, a direct measurement and comparison of the widths and differential cross sections of forward and reversed quantum transitions has some difficulties. This is due to the fact that the spectral width of a quantum transition from one state to another is usually associated with the lifetime of these states relative to spontaneous emission. If the lifetime with respect to spontaneous emission is large, then the spectral width is very small and vice versa. This makes it difficult to separately study the characteristics of forward and reversed processes. But, as we shall see below, such a connection is sometimes violated.

Besides that, today we have in this field a huge number of quite obvious direct and indirect experimental evidence of nonequivalence of forward and reversed processes in quantum physics. Here the short review of the main direct and indirect experimental facts of asymmetry in time of physical laws in quantum physics.

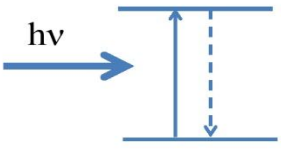
Population transfer in a two-level system.

It is usually believed that the non-linear optics emerged after the invention of such powerful sources of radiation as lasers. However, the main mathematical model of nonlinear optics, which describes interaction of two-level system with a resonant radiation had appeared even earlier. The famous Bloch equations were proposed in 1946 to describe the dynamics of two-level system in nuclear magnetic resonance [7]. Now Maxwell-Bloch equations are used for the description of many nonlinear effects in optics. Such model gives really good description of the optical phenomena [8, 9]. However the Bloch equations have not clear physical interpretation. Therefore there are large difficulties at attempts to understand physical sense of such descriptions.

For a long time and strongly settled opinion exists that forward and reversed optical transitions are equivalent, and electromagnetic interactions as a whole in nature are time reversal invariant [10]. It is difficult to understand what is the base of this opinion. Usually it is referred to Einstein's opinion "that physics could be restricted to the time-symmetric case for which retarded and advanced fields are equivalent" [11].

The basis of this opinion can not be the equality of Einstein coefficients for absorption and stimulated emission of photons. Einstein coefficients characterize the integrated cross-section of optical transition. The preservation of time reversal invariance demands not only equality of integrated cross-sections, but also equality of spectral width of direct and reversed optical transitions. Thus, the equality of Einstein coefficients have not the direct relation to time reversal invariance of process of photon absorption.

The brightest indirect proof of this inequality in our opinion is the effect of adiabatic population transfer in two-level system due to sweeping of resonant conditions [12]. When the resonance radiation interacts with the two-level system, the so-called periodical Rabi oscillations of the levels population takes place. But if the sweeping of resonance conditions appears (for example, the frequency of radiation is changed), the full population transfer from the initial level to the opposite one happens (Fig. 1). And this result does not depend on intensity of radiation. This surprising result is well described in Bloch model. It is said, that the physical nature of this effect can hardly be explained verbally in simple terms, but one should carefully follow the behavior of the vectors in the model of the rotating wave [13]. This situation resembles very much an appeal of the prestidigitator asking the spectators to watch his hands carefully while he is making the manipulations. And the result seems to be the same. An "explanation" is given, but its physical essence is absolutely unclear.



Dynamics of two-level quantum system

Bloch equations 1946

resonance conditions = Rabi oscillations - case of symmetry

sweeping of resonance conditions = irreversible transfer of population from initial on final level - case of asymmetry

Fig. 1 On the mathematical description of dynamics of two-level quantum system

This is a fantastic situation. We deal with extremely simple quantum system. This is a very simple physical phenomenon that has been studied thousands of times in different ways.

This phenomenon has a beautiful mathematical description. But it does not have any physical explanation. Even stupid, nonsense physical explanation is absent till now. Why a fully symmetric case turns into a completely asymmetrical? This situation lasts for more than 70 years - is only slightly less than that for quantum mechanics as a whole.

Here it is important that the physical explanation of this effect is impossible, if we assume equality forward and reversed processes. There has to be some difference so that the atom can know which level is the initial and which level is the final. It is natural to expect, that the difference can consist in different width and cross-section of forward and reversed transitions. So, the rapid adiabatic population transfer effect is the most convincing indirect proof of inequality forward and reversed processes.

However, for the decision of the problem only indirect proofs are insufficient. The direct proofs are necessary. And such direct proofs exist for many years. One of its is connected to physical object, which has an unusual combination of properties: extremely large homogeneous width of optical transition is combined with the big lifetime of the exited state toward to spontaneous emission. In this case it appears very easily experimentally to find out the large difference between parameters of forward and reversed processes. This unusual object is the so-called wide component of line in absorption spectrum of polyatomic molecules. The following section is devoted to discussion of experiments with this object.

Direct experimental proofs

1. Infrared multiple photon excitation of polyatomic molecules

The phenomenon of the infrared multiple–photon excitation (IR MPE) and collisionless dissociation of polyatomic molecules was discovered in works [14, 15]. It was founded, that polyatomic molecules can absorb tens photons of laser radiation and dissociate without collisions. Numerous works were carried out later aimed to clarify the mechanism of this process. This interest was stimulated by the fact, that the widths both of laser radiation and molecule absorption lines are substantially lower, than the anharmonicity of molecular vibrations. It means, that the absorption of second quantum of laser radiation should not occur.

For an explanation of the mechanism of process in the former work the hypothesis about existence of so-called ”quasicontinuum” of vibrational states was proposed. It was proposed, that ”quasicontinuum” consists of a huge number of narrow lines arising as a result of coupling different vibrational states. Despite of the argued criticism [16] such idea has received the

broadest distribution. Late, however, the views on the nature of ”quasicontinuum” have changed dramatically.

Now it is widely believed [17], that the absorption line is unique, but it becomes very wide. The origin of the ”quasicontinuum” now is bounded up with intramolecular vibrational relaxation (IVR) process. This is a reasonable idea. The IVR process can be very fast (picoseconds timescale). The corresponding Lorentzian width of the absorption line can be in this case comparable with anharmonicity of the molecular vibrations. The main disadvantage of this model is that it does not explain how the molecules can be excited in the region of low vibrational levels, where the IVR is absent and the absorption lines remain narrow. Experiments show, that excitation of molecules in this area occurs without essential difficulties, but the theory gives no satisfactory explanation of this fact.

In works [18] an idea was proposed, that the IR MPE process is a trivial result of absorption in the area of line wings, but untrivial is the nature of these wings. The possible role of line wings practically was not discussed in the literature earlier. It is, apparently, due to the fact, that appropriate estimations can easily be made. The lifetime of excited states of molecules due to spontaneous emission in the infrared region lays in the millisecond timescale. The natural width of line must to be smaller than 100 Hz. Even for the strongest molecular transitions, at the distance from the line center equal to the value of molecular anharmonicity, the Lorentzian contour of the natural width would have an absorption cross–section smaller then 10^{-25} cm^2. This cross–section cannot play any appreciable role in overcoming the anharmonicity of molecular vibrations.

However, such estimation has not been tested in experiment earlier. It is possible to assume, that for some unknown reasons, intensity of real line wings is much higher, than the theory predicts. How high the intensity of line wings should be to explain the observable effect of laser excitation of molecules? Rather correctly such information can be derived from the experimental results of works [19-21], where the depletion of rotational states of SF_6 molecules by TEA CO_2–laser radiation was studied in the conditions of molecular jet. The results of such processing are presented in Fig. 2. Except for the usual narrow component of the line with a Doppler width ~ 30 MHz, the wings, or more precisely speaking, a wide component of the line should exist with a cross–section ~ $6 \cdot 10^{-20}$ cm^2 and with a Lorentzian full width at half medium ~ 4.5 cm^{-1}. The relative integral intensity of this component is rather small, ~ 0.2 %, but it is high enough for efficient excitation of molecules from all rotational states.

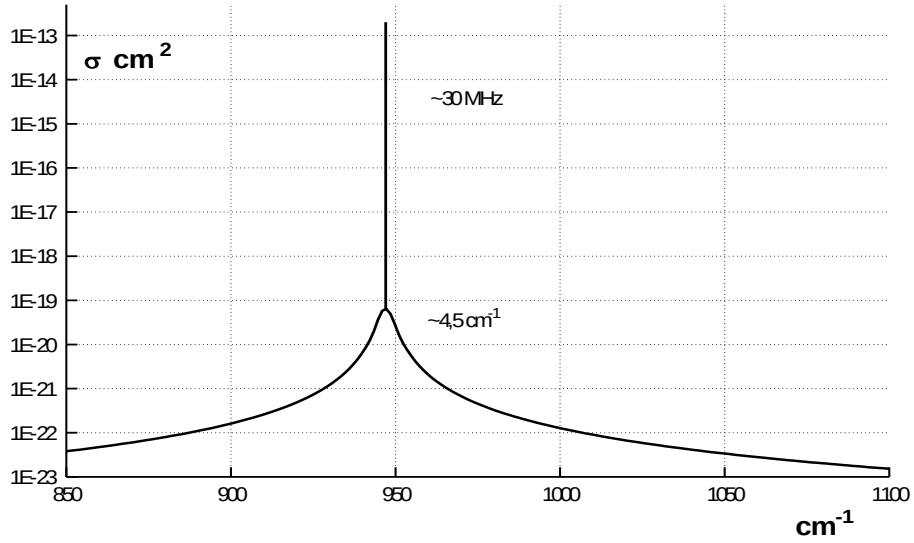


Fig.2 Profile of absorption line of SF_6 molecules for ν_3 band 1---0 transition.

For experimental test of existence the wide components of a line the form of line should be studied on the large depth. This strongly prevents by inhomogeneous broadening, which connected with distribution of molecules on different rotational states. At room temperature the dense spectrum of transitions from different rotational states is observed. But here it is important to pay attention that Lorentzian contour is rather flat and wide component of lines can manifest itself as far natural wings of absorption bands. There are many publications about study of far wings of absorption bands of small and light molecules [22, 23]. These wings are the result of collisional broadening of absorption lines.

For heavy polyatomic molecules in a gas phase the far wings of absorption bands of other nature were discovered in work [24]. The experiments have shown that the cross-section of absorption in the region of these wings does not depend on pressure of gas. So, it has a natural nature.

In Fig. 3, the spectral dependence of the absorption cross-section of SiF_4 molecules around the $\mathbf{\nu_3}$ absorption bands is presented (curve 1). The edges of the absorption band have approximately an exponential form, the slope being greater for the blue side, than for the red one. At the distance more, than 25÷40 cm^{-1} from the band center, much more flat wings are observed. The curve (2) is a Lorentzian profile with FWHM = 4.5 cm^{-1}, which passes through the point with minimal absorption cross-section in the given spectral range. So, we can see that the far band wings have a Lorentzian form. In Fig. 4 a spectral dependence of the absorption cross-

section of SF_6 molecules is shown. In this rather typical case the far band wings are masked by intense combination bands.

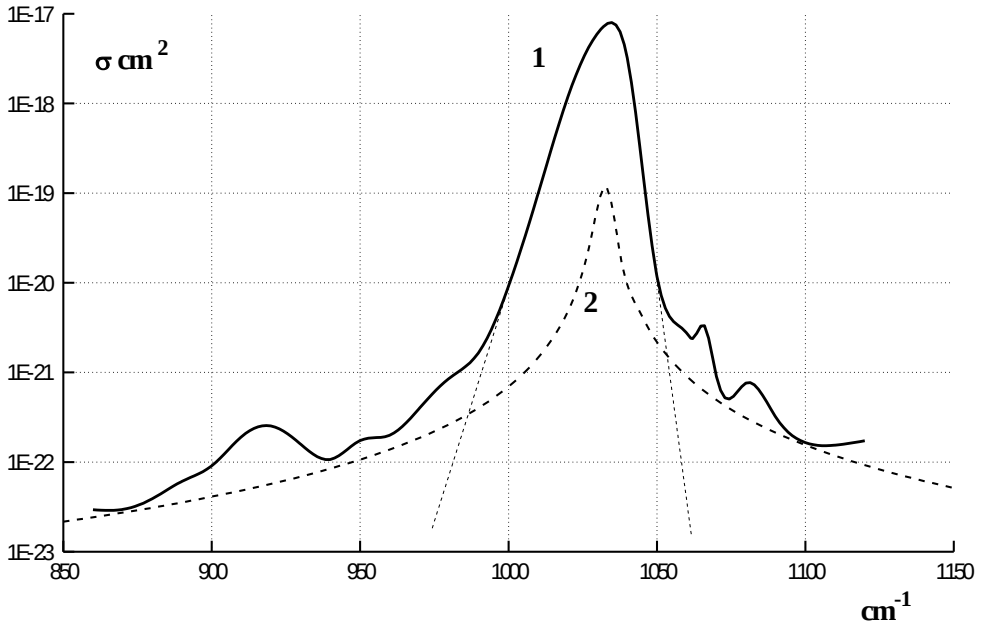


Fig.3 Spectral dependence of the room temperature absorption cross-section of SiF_4 molecules.

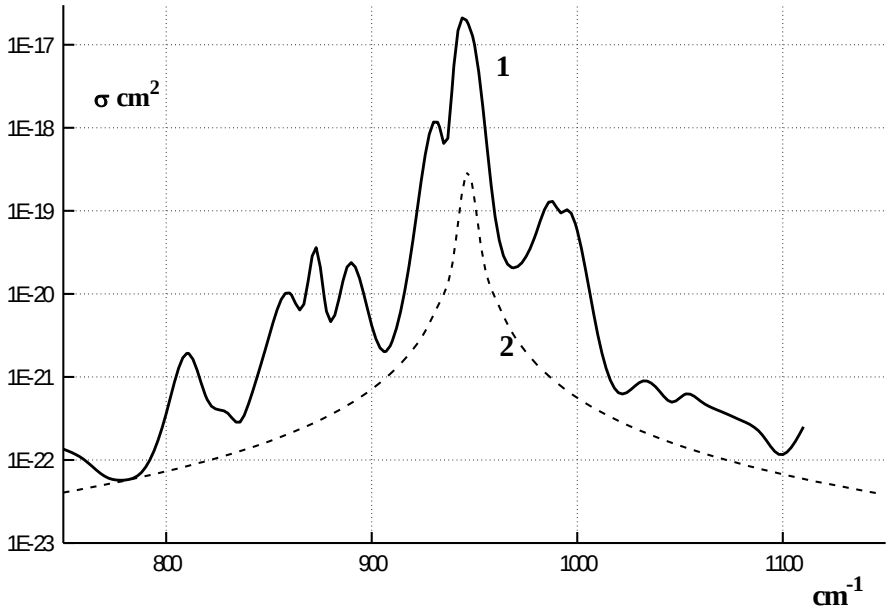


Fig.4 Spectral dependence of the room temperature absorption cross-section of SF_6 molecules.

The measurement of intensity of far absorption band wings allows to estimate integrated intensity of wide components of lines. The same value can also be experimentally estimated by other method: on the data about saturation of absorption spectrum of polyatomic molecules by radiation of pulse CO_2 laser at low gas pressure [24]. The experiments show, that the relative intensity of wide component quickly grows with increasing of number of atoms in a molecule and branching degree of the molecules. Thus the estimated average relative integral intensity of the line wings at room temperature varied from ~ 0.6 % for SF_6 and SiF_4 to ~ 90% for $(CF_3)_2O$ and $(CF_3)_2CO$.

A substantial difference exists between the estimations of the relative integral intensity of the line wings for SF_6 molecules, derived from works [19-21] (~ 0.2 %) and obtained in [24] (~0.6÷0.8 %). This is obviously due to the fact, that in the first case the molecules were located at a zero vibrational level, and the second estimation is obtained for the room temperature, when the majority of molecules is in different excited states. The strong temperature dependence of the laser radiation absorption by SF_6 molecules [25] allows to assume, that the intensity of line wings substantially grows with increasing the level of vibrational excitation of molecules. This is maybe the main physical reason of formation of ensembles of ”hot” and ”cold” molecules under action of the pulse CO_2 laser radiation [26].

The nature of wide components of lines is unknown. As a hypothesis the following explanation is offered. A certain mechanism of averaging of the rotational moment of molecule inertia works during the vibrational motion of atoms. In large molecules, this mechanism undergoes periodic and reversible destruction. As a result the absorption line splits on a clump of narrow lines, and the short-lived moments of breaking correspond to a wide component of a line [27].

The wide component of line is unique physical object, which has the long lifetime of the excited states toward to spontaneous emission and large homogeneous spectral width of optical transition. This combination of properties is very convenient for study the reversed optical transition in conditions of a molecular beam.

The wide component of lines was easily observed in work [25] at study the absorption by SF_6 molecules of radiation of continuous CO_2 laser in a molecular beam with cryogenic bolometer. Rotational temperature in a molecular beam is very low (~ 5^0 K). It radically changes character of a molecule absorption spectrum. The absorption lines become very rare and the CO_2 laser radiation interacts practically only with the wide component of lines. Unfortunately, the authors had not understood with what thing they deal with and later the work with this object was closed.

In present case we are not interested in a line wings itself, but in the results of double optical resonance experiments in a molecular beam [25]. For the first laser beam the absorption spectrum represents wide continuum. For the second laser beam, which cross the molecular beam later, besides this wide continuum a sharp dip with a width ~ 450 kHz is observed. It characterizes a spectrum of the reversed optical transition. The ratio of forward and reversed optical transitions widths exceeds 10^5 times for the given case.

Besides this, the amplification of probe laser radiation was observed. Taking into account, that in some of these experiments the number of the molecules, exited by the first laser, did not exceed ~ 0,1 %, it is a typical case of amplification without inversion. Thus the cross-section of the reversed optical transition should be at least on three orders of magnitude more, than of forward one. Because of the Einstein coefficients for forward and reversed transitions should be equal, the present estimation for cross-section of the reversed transition is, obviously, underestimated.

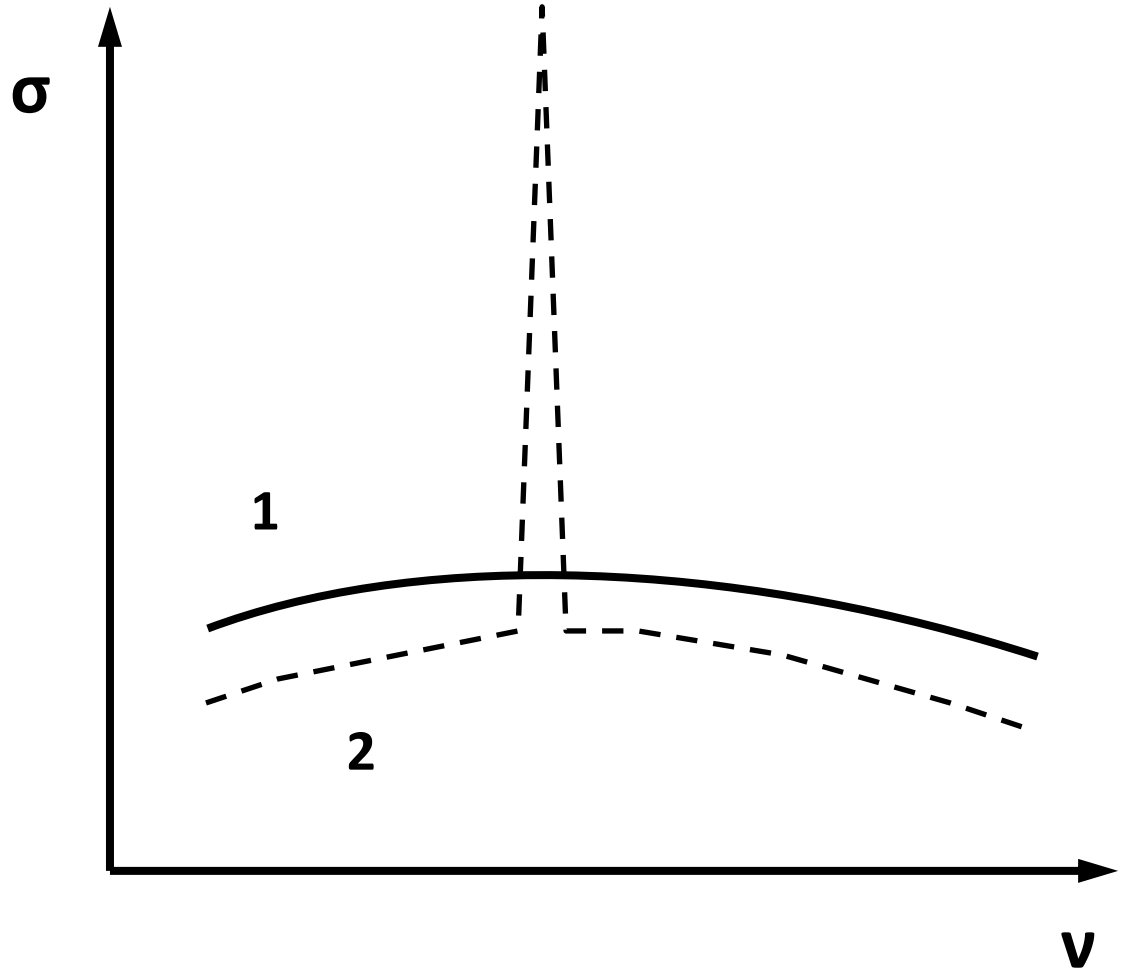


Fig. 5 The supposed shapes of dependences of cross-sections for absorption (1) and stimulated emission of photon (2) in the region of far wings of absorption line.

So, there is infrared multiple photon excitation of polyatomic molecules phenomenon. Here the excitation of molecules by laser radiation occurs through the unexpectedly intense far wings of the absorption lines. It is important that this is a real continuum of absorption. With this in mind, the other pump-probe experiments in molecular beams directly and clearly show that the forward and reversed processes are very different from each other (Fig. 5). According to the spectral width, they differ by five orders of magnitude. And the evaluation of the difference of differential cross sections gives value more than three orders of magnitude.

The discussed above experiments, can be considered as the direct and complete proof of the time reversal invariance violation in quantum physics.

2. Bloch oscillations of cold atoms in a vertical optical lattice

Other direct and clean experimental proof of time reversal noninvariance is well-known Bloch oscillations of cold atoms in a vertical optical lattice [28, 29]. Here cold atoms fall freely in a vacuum under gravity. The vertical optical lattice is formed by two oppositely directed laser beams. According to the existing theoretical concept the physical base of the Bloch oscillations is the polarization interaction of the atoms with the standing optical wave. This proposed physical explanation assumes that antinode of a standing wave are potential barriers which can reflect atoms. But there are no reliable experimental proofs of existence of such barriers. This is only a hypothesis.

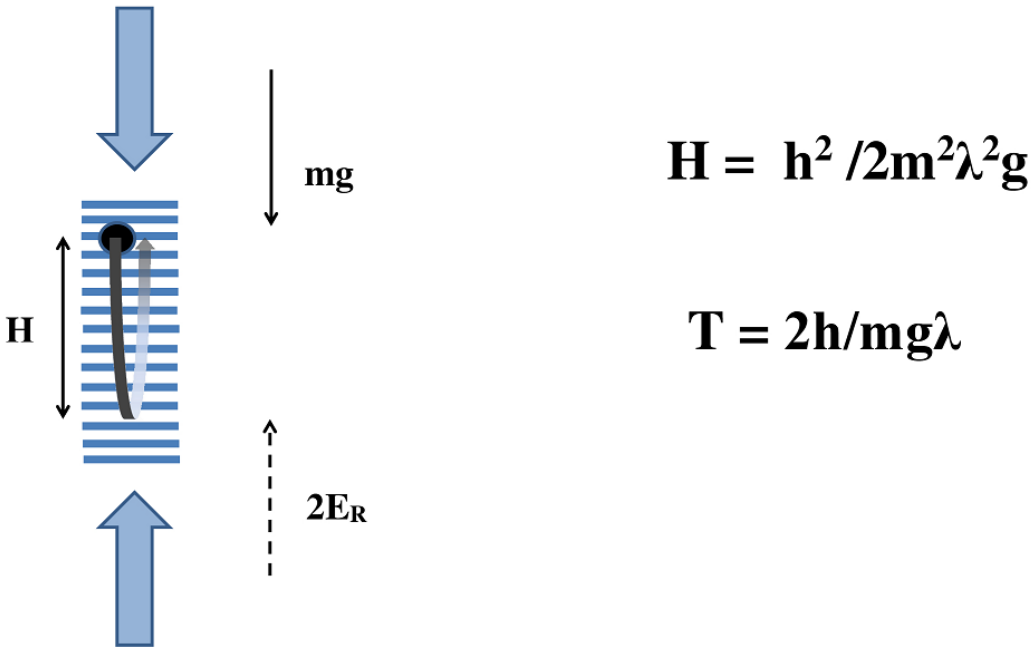


Fig. 6 Scheme of the Bloch oscillations of cold atoms in a vertical optical lattice**.**

The main problem of this explanation is that the amplitude of oscillation of the atoms does not coincide with the period of the optical lattice. This amplitude is usually much greater than the lattice period. Then you have to assume the existence of the so-called superfluid regime, when the atoms are able to tunnel through a number of potential barriers.

Of course, there is a beautiful mathematical description of the phenomenon based on the Gross-Pitaevskii equation [30, 31]. But this description in direct or indirect way assumes that the motion of atoms in an optical lattice is due to the spatially asymmetric scattering of photons. At the certain moment of time the Raman optical transition takes place. The atom absorbs a photon from the upward beam and emits a photon in the direction of downward beam. As a result, the atom receives double recoil momentum and returns to the starting point of the space (Fig. 6). From this the formulas for the amplitude and period of oscillations are derived. The obtained recoil energy ($2E_R$) allows for atoms to stop and to return in the initial point. The amplitude (height) of atomic oscillations (H) may be deduced from condition $E_R = h^2/2m\lambda^2 = mgH$ and it is given by

$$H = \frac{h^2}{2\, m^2\, \lambda^2\, g} \qquad (1)$$

where m is the atomic mass, g is the acceleration of gravity, λ is the wavelength of the light, and h is Planck constant.

For ^{88}Sr and λ = 532 nm this height equals 3,66 μm or 6,88 λ [28]. For ^{40}K and λ= 873 nm it equals 6,57 μm or 7,5 λ [29, 32]. But for ^{7}Li atoms this value reach 150 μm or ~ 300 lattice sites (for λ = 1064 nm) [33]. It is ridiculous to speak about potential barriers here. The wavelength of the laser radiation (λ) is included in these formulas because it affects the magnitude of the recoil momentum. If to raise the installation from the first floor of the building to the second, then the point of atom's reflection will shift because of the gravity changes. The measurement of oscillating frequency allows a sensitive determination of the acceleration of gravity or forces at the micrometer length scale. This phenomenon is now widely used to measure gravity and its gradient [28, 29].

The fall time (t) of atoms is related to the height by $H = gt^2/2$. So, for the period of oscillations (T) we obtain:

$$T = 2t = \frac{2\, h}{m\, g\, \lambda} \qquad (2)$$

Thus, we have two different explanations of the physical nature of the phenomenon: the presence of potential barriers in an optical lattice and a highly spatially asymmetric scattering of photons. If two opposite ideas coexist in one head, then the doctors, seem, call it as schizophrenia. But our scientists feel themselves fine in this state. They talk about potential barriers, double well, tunneling and use the mathematical model which is based on the fact of a highly spatially asymmetric scattering of photons. At the same time, there are no reliable experimental proofs for the existence of potential barriers in an optical lattice. We have a situation when the quantum phenomenon is tried to be explained on the basis of the principles of classical physics. It is obvious that the idea of potential barriers in an optical lattice is the myth, phantom. In reality, we have the experimental fact of high spatial asymmetric scattering of photons, which is a direct consequence of the enormous inequality of differential cross sections of forward and reversed processes.

So, today the Bloch oscillations of cold atoms in a vertical optical lattice are the cleanest and most convenient model for experimental studies of a fully reversed quantum transition.

3. Mixing of entangled photons

The down-conversion process is the easiest and most widely used way to get entangled photons. Here, one photon splits into two photons in a nonlinear crystal. The resulting entangled photons demonstrate amazing properties that quite directly indicate a huge inequality in the differential cross sections of the forward and reversed processes in quantum physics.

One clear and direct experimental proof of nonequivalence of forward and reversed processes is published in [34]. Although, the authors do not discuss this problem. Here, the forward (splitting) and reversed (mixing) processes with a photons were studied (Fig.7). On the first stage the narrowband (0.04 nm) radiation of nanosecond laser was transformed through down-conversion in the nonlinear crystal into two broadband signal and idler beams (each spectral width ~ 100 nm). On the second stage this two broadband beams were mixed in the sum frequency generator (SFG). It is expected that by mixing the two beams with a broad spectral distribution the beam with even broader spectral distribution will appear. However, the experiments show that in this case the mixing of entangled photons leads to regeneration of initial narrowband radiation and this is the example of reversed process into the initial state. In contrast, the mixing of non-entangled photons should give broadband radiation and this is the

example of only forward process. The experiment shows that the efficiency of reversed process is much greater, than the efficiency of forward process.

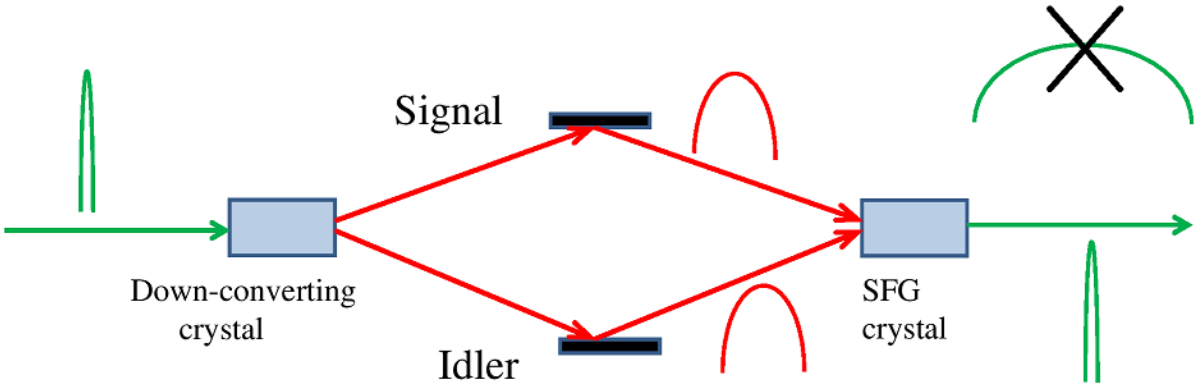


Fig. 7 Scheme of the experiments for splitting and mixing of photons in nonlinear crystals

Another variant of this experiment is the so-called entangled two-photon absorption (ETPA). Conventional two-photon absorption (TPA) was discovered after the invention of lasers. It occurs at a very high radiation intensity. In contrast, two-photon absorption of entangled photons by molecules is observed at radiation intensities of 6 - 10 orders of magnitude less [35 - 37]. This result inspires chemists and biologists - they can study the two-photon excitation of molecules at very low radiation intensity. However, physicists must explain the nature of this phenomenon. And this explanation is very simple. The formation of entangled photons is a forward process, and their absorption by a molecule (equivalent to the regeneration of the initial photon before down-conversion) is a reversed process that has a large differential cross section.

The experiments [35 - 37] were carried out with large molecules. Similar experiments with ETPA in rubidium atoms were performed in [38]. Excellent results were obtained. These experiments also demonstrate a strong dependence of the efficiency of the reversed process on the phase of radiation. Unfortunately, a simple and important thing was missed in this work: there is no experimental comparison of the effectiveness of the observed ETPA with the conventional TPA.

There is another variant for mixing entangled photons. This is the widely known Hong-Ou-Mandel (HOM) effect, discovered in [39]. Fig. 8 shows the schematic diagram of the

experiment. In the nonlinear crystal, the initial photon is split into two - signal and idler. The beam splitter directs falling photons randomly to a particular detector with a 50:50 probability. However, when the path lengths of the signal and idler photons coincide, this randomness disappears and both photons jointly arrive at one of the detectors. This is the surprising essence of the discovered phenomenon. Its physical explanation is still missing.

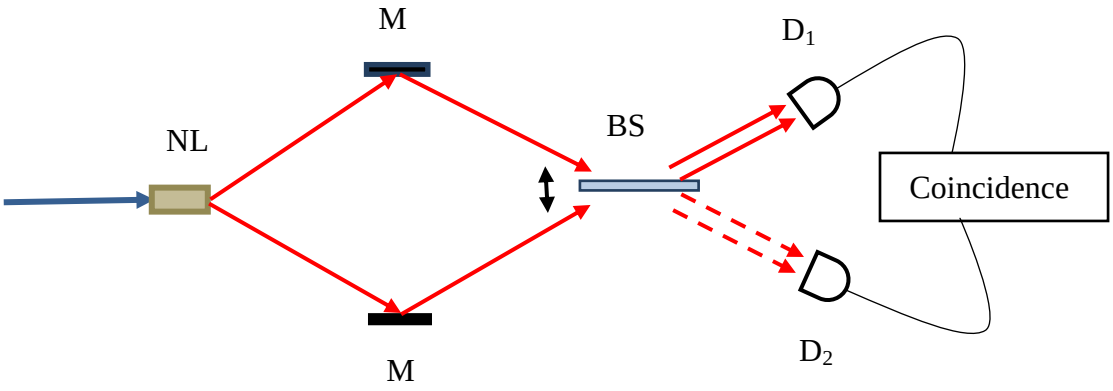


Fig. 8. Schematic diagram of the experiment. NL – nonlinear crystal, M – mirror, BS - beam splitter, D_1 and D_2 – detectors.

Our physical explanation is that here we are again dealing with a reversed quantum process. There is no regeneration of the original photon. This process is not fully reversed. But the signal and idler photons are synchronized in time, phase; combined in space and direction. This is a partially reversed quantum process. The following hierarchy of differential cross sections for fully reversed (σ_{FR}), partially reversed (σ_{PR}), and forward (σ_F) quantum processes is obviously fulfilled:

$$\sigma_{FR} \gg \sigma_{PR} \gg \sigma_F \qquad (3)$$

4. Spatially asymmetric scattering of light and optical precursor.

One more direct proof of nonequivalence of forward and reversed processes is the results of experiments on the scattering of light by cold atoms. In work [40] the authors observe in ultracold ^{88}Sr atoms the highly directional forward emission with a peak intensity that is

enhanced by $>10^3$ compared with that in the transverse direction. Such forward directed scattering is the closest case to a fully reversed quantum transition. After the photon is radiated forward, the atom remains at the starting point of space, and the quantum system returns to its initial state (before the photon is absorbed). Due to the very large differential cross section for forward scattering (σ_{FR}), radiation can pass through the medium with almost no absorption.

This property, obviously, is the physical base of such a phenomenon as an optical precursor. An optical precursor is usually called the leading edge of a laser pulse, which passes through an absorbing medium with minimal absorption [41, 42]. As usual, we have variants of a good mathematical description of the phenomenon [43 - 45]. However, there is no satisfactory physical explanation for it.

The inequality of the differential cross sections of the forward and reversed processes is a good physical explanation of this phenomenon. Interestingly, how it can explain the duration of the optical precursor. During the time between the absorption of the photon and its forward emission, the atom moves from the starting point of space. Accordingly, the phase of the radiation also changes. Photon emission is no longer a completely reversed process. Its differential cross-section drops. This determines the duration of the optical precursor.

The speed of phase change should depend on the wavelength of radiation and the speed of movement of atoms or molecules. Then we can expect that the duration of the optical precursor (τ) will be proportional to the radiation wavelength (λ) and inversely proportional to the atomic velocity (υ) or the square root of the gas temperature (T):

$$\tau \sim \lambda/\upsilon \sim \lambda/\sqrt{T} \qquad (4)$$

The phenomenon, which is now called an optical precursor, was first observed experimentally, apparently, in the work [46], where the authors studied the passage of a picosecond radiation pulse (λ=5890Å) through an optically dense hot sodium vapor. The first undelayed pulse corresponding to the optical precursor had a duration of about 10 picoseconds.

Further, the optical precursor was observed in a warm HCN molecular gas for a step-modulated field propagating with a wavelength of 3.5 mm [47, 48]. Here the wavelength of the radiation was approximately $6 \cdot 10^3$ times greater than in [46]. According to (4), the duration of the optical precursor in this case can be expected to be about 60 nanoseconds. And this is close to what is observed in the experiment (Fig. 9).

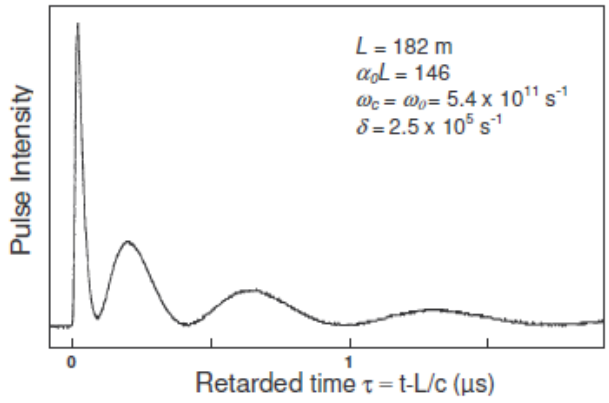


Fig. 9 Optical precursor in [47, 48]

Later, the optical precursor was studied in the cold atomic gas of K (λ=770 nm, ~ 400 μK) [41] and Rb (λ=780 nm, ~ 100 μK) [42]. In these cases, the temperature of the atomic gas was more than six orders of magnitude less than in [46]. In accordance with (4), it can be expected that the duration of the optical precursor under these conditions should be about 10 nanoseconds or slightly longer. Figure 10 shows that the experimentally observed duration of the optical precursor is enough close to this estimation.

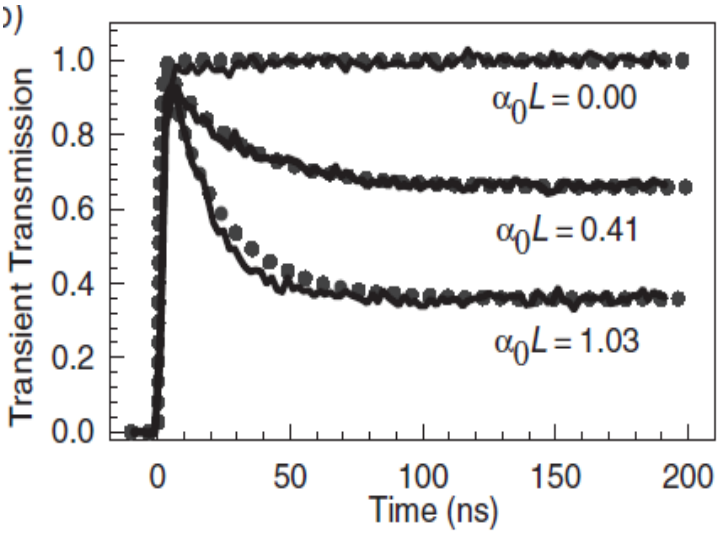


Fig. 10 Optical precursor in [41]

Thus, the idea of the nonequivalence of forward and reversed processes in quantum physics provides a quite good physical explanation of the ratio of the durations of optical precursors observed in [41, 42, 46, 47].

On the other hand, spatial asymmetry of light scattering clearly demonstrates probable physical mechanism of subrecoil laser cooling process: *spatially asymmetric photon scattering tries to preserve atoms at the initial marked point of space.*

Other indirect experimental evidences

Four-photon mixing

The traditional explanation of a nature of nonlinear optical processes has descriptive character. Their existence is connected with so-called nonlinear susceptibility of atoms and molecules [49]. If appropriate factor of a nonlinear susceptibility is great enough, the process, for example, of a wave mixing can occur. If this factor is equal to zero, the wave mixing is absent. Also, some restriction exists, which is connected with the symmetry of the process, phase matching. What physical property leads to the requirement of symmetry and phase matching? The answer is absent.

The origin of the number of phenomena in nonlinear optics also usually is explained on the basis of interference. This is not because of the concept of interference gives reliable physical explanation of its nature, but because of any suitable alternative variant was absent.

The nonequivalence of forward and reversed processes is such an alternative. As an example, it is possible to discuss a situation with three and four-wave mixing in nonlinear optics. In a gas phase processes of four-photon mixing are observed and there are no processes of three-photon mixing. In the solid phase, by contrast, processes of three-photon mixing prevail.

The simplified scheme of the experiments of a four photon mixing in the so-called BOXCAR arrangement is shown for the most common case [50, 51]. Three different directed laser beams intersect at one point. Its radiation transfer the molecules (or atoms) from the initial level **a** on the quantum level **d** (Fig. 11b). Then the directed spontaneous superfluorescence appears and the molecules return into the initial state. The direction of the superfluorescence does not coincide with the directions of the laser beams and it is easily separated. The dependences of the superfluorescence intensity from the delays between the laser pulses allow studying the dynamics of vibrational and rotational motions of molecules on the different quantum levels **b**, **c**. The superfluorescence is the consequence of the final stage of the transition of the quantum system into the initial state. This transition characterizes the properties of the reversed processes: extremely high differential cross-section of the optical transition and its space anisotropy. Therefore, such experiments are the indirect proof of radical difference of the

reversed optical transitions from the forward one: the existence of space and phase anisotropy of the reversed transition. For the forward transition such anisotropy is not characteristic.

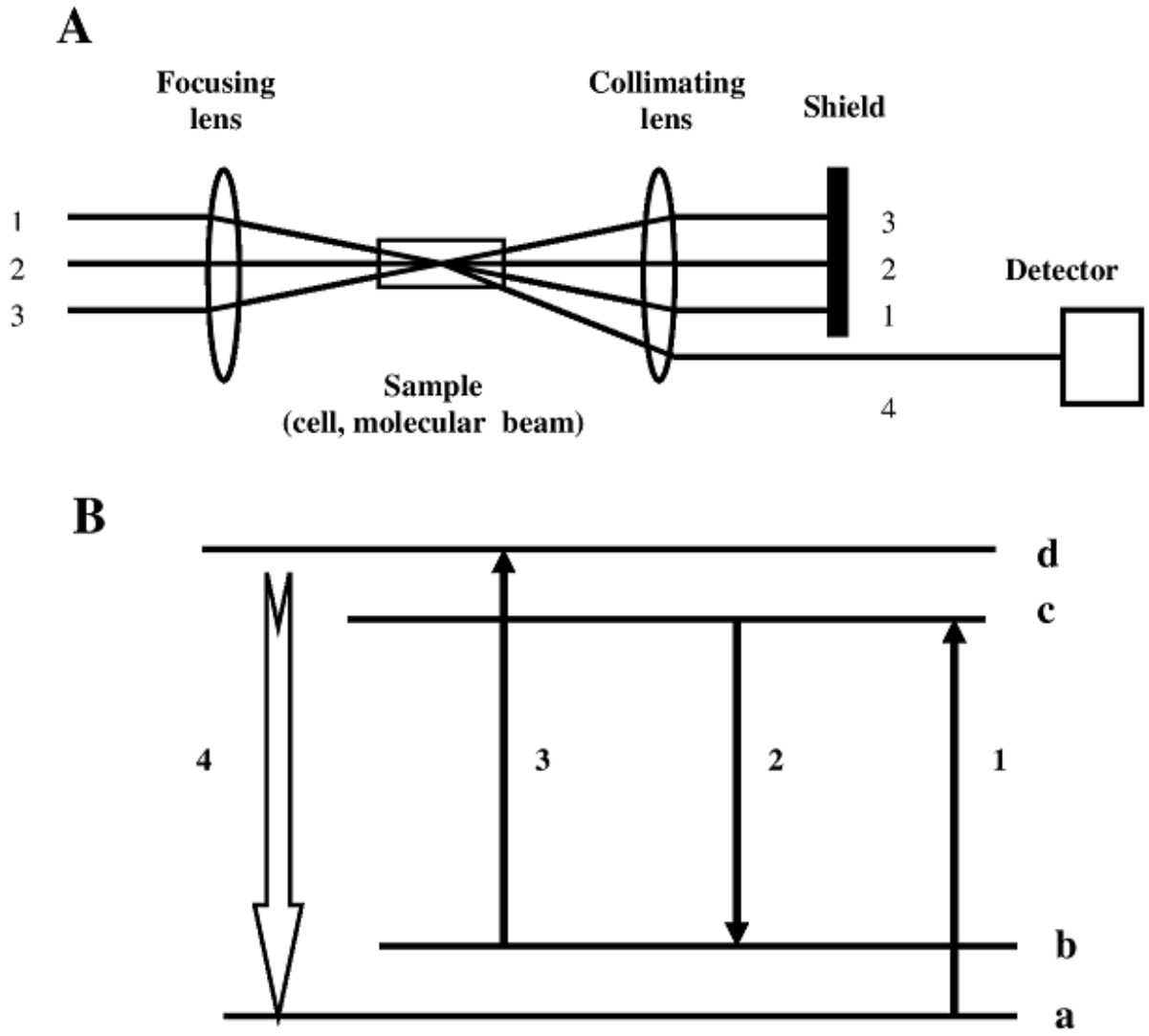


Fig. 11 A) Experimental setup showing the beam path of the BOXCAR arrangement for a four photon mixing. **B**) Energy level diagram.

In this case it becomes clear why in gas and liquid phases there are no effective processes of three and five photon mixing. Each photon has a spin. If we have an odd number of photons, it is impossible to return the quantum system (atom, molecule) exactly into its initial state. With even number of photons, it is possible. At the same time in crystal lattice, where the rotation can be suppressed, such processes with odd number of photons are quite effective. The requirement of phase matching has a similar explanation.

Coherent Population Trapping - Electromagnetically Induced Transparency

The phenomenon of Coherent Population Trapping (CPT) or Electromagnetically Induced Transparency (EIT) in the most ordinary case is studied in a cold atomic gas with a three-level Λ scheme under the influence of resonant radiation of weak probe and strong control laser pulses [52, 53]. Spontaneous fluorescence from the excited level (c) or transmission of a weak probe pulse are recorded (Fig. 12a). In resonance conditions, a decrease in the intensity of spontaneous fluorescence and a decrease in the absorption of probe radiation are observed.

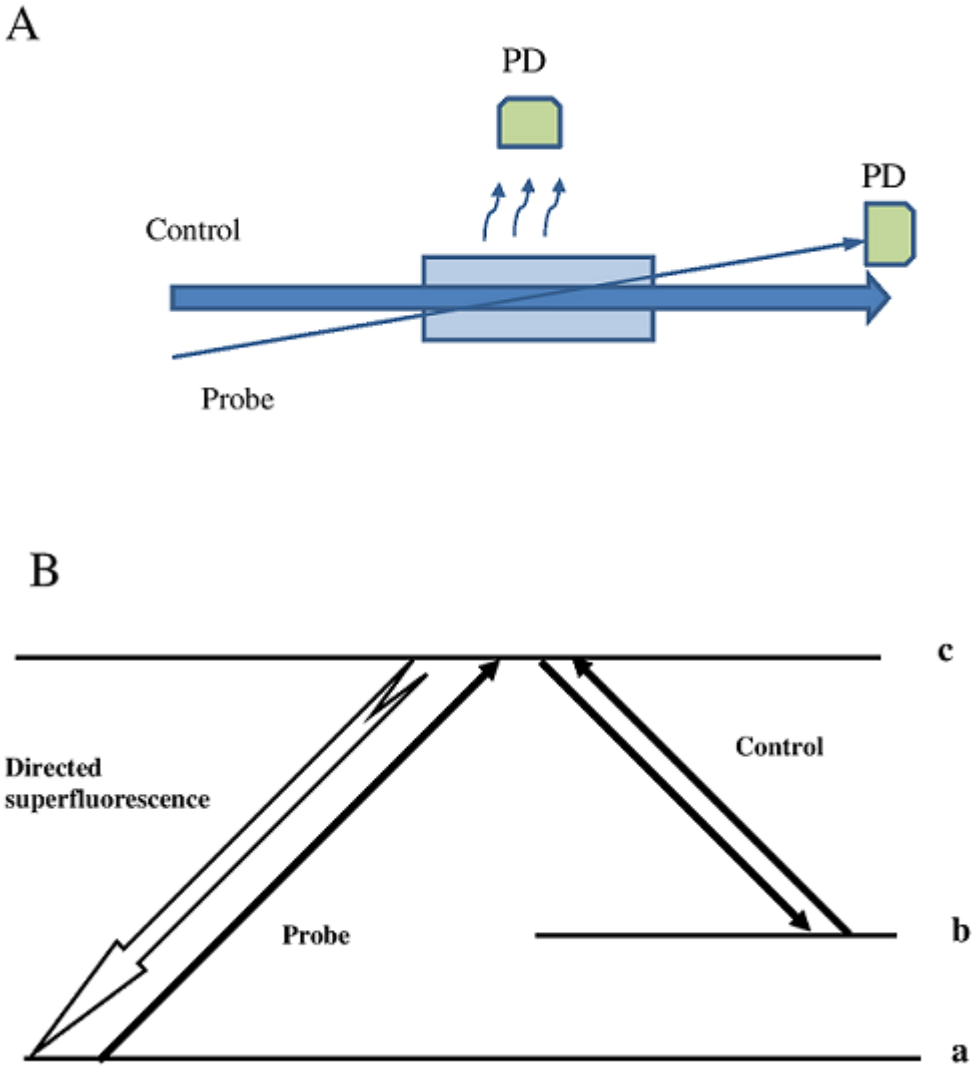


Fig. 12 **A**) Experimental set-up for observing CPT-EIT phenomenon in cold atoms. **B**) Energy levels diagram for four-photon mixing process.

It is assumed that quantum interference modifies the optical properties of the atomic system in such a way, that the so-called dark states appear, which are a coherent superposition states and nullified an atomic-light interaction operator [54]. In the dark state the atoms neither absorb nor emit a light.

It is a wrong explanation. The matter isn't that atoms don't absorb radiation, but that they radiate it very well when they transfer to the initial state. This is again the result of the multiple stage of four-photon mixing process (Fig. 12b). The final transition has a very large differential cross section and it is a directional superfluorescence. It regenerates the probe radiation. This is clearly seen in the experiments with the additional delayed control pulse [55].

Field-free alignment of molecules

In recent years it has become a popular to study the phenomenon of the so-called field-free alignment of molecules [56]. There is a very powerful nonresonant femtosecond pump pulse affects the molecular gas. Then, the gas is probed with a very weak delayed pulse. As a result, the short bursts of interaction of probe radiation with gas are observed (Fig. 13). With a frequency, which is multiple to the quantum period of rotation of molecules.

However, the effects here are divided into two types: passive (geometrical) and active (dynamic) alignment [57]. The concept of geometrical alignment is connected with the generally recognized opinion that the probability of optical transition depends on orientation of the molecule in space relative to the direction and polarization vector of the laser beam [58].

The dynamic alignment effect usually is connected with the assumption that intense laser field is capable to create the certain orientation of molecules in space. It is supposed, that the dipole moment induced in a polarizable molecule by the laser field can hinder free rotation of molecules. Molecules appear in the so-called pendular states, in which the molecular axis librates about the electric field vector. When the laser radiation is switched off, the molecules continue free rotation at an initial speed [56]. The situation is interesting, because of any reliable experimental proofs of existence of the dynamic alignment effect are absent. Such assumption seems fantastic. There is again the attempt to explain quantum phenomenon with the help of the concepts of classical physics. Our physicists, probably, understand that it is full nonsense, but they don't see any alternative explanation.

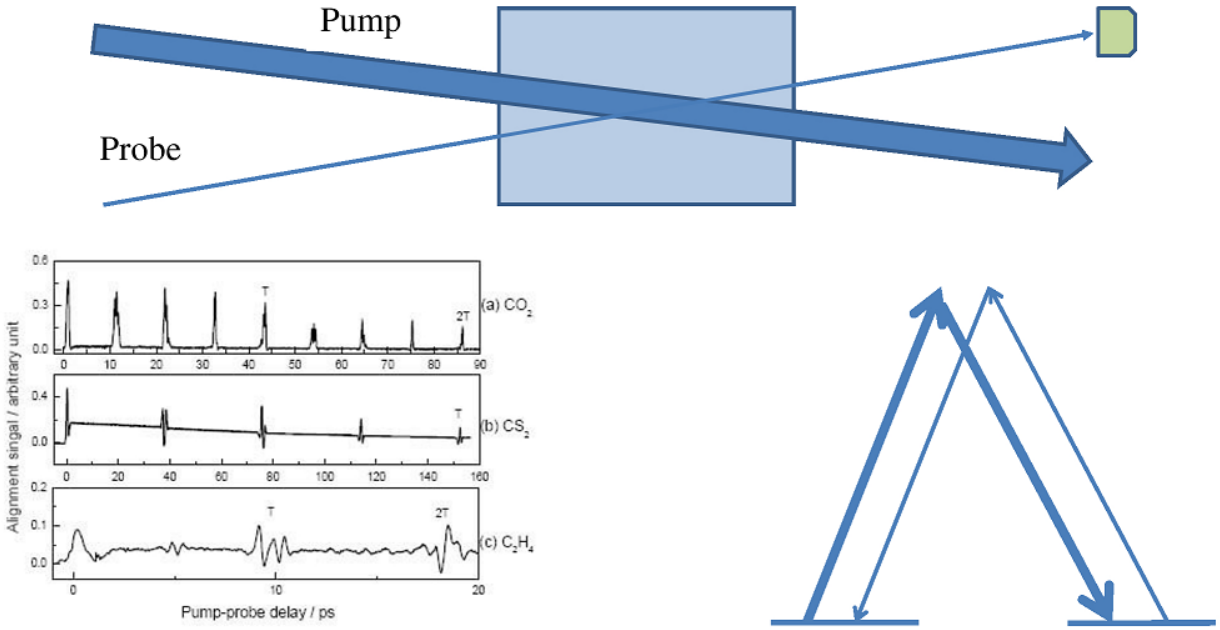


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Fig. 13 Experimental set-up for field-free alignment experiments.

However, we can easily find an alternative physical explanation, if we recognize the fact of inequality of forward and reversed processes in quantum physics. On the basis of such inequality the physical nature of the discussed above phenomenon is very easily and naturally explained [59]. Under action of the pump pulse the forward Raman transitions between the lowest degenerated levels of molecules occur. And the weak probe pulse creates reversed into the initial quantum state transition with high differential cross section. This transition happens only at the same orientation of the molecule as upon the forward transition. Any stop of molecular rotation is not required.

All this discussed direct and indirect experimental evidences clearly show inequality of forward and reversed processes in quantum physics. An extremely large and sharp differential cross-section of reversed transitions is the real physical base of nonlinear optics. There are many other phenomena in nonlinear optics (atom interferometry, high harmonic generation, photon echo, etc.) that have a similar explanation. May be a little less obvious.

Main consequences

The main consequence of the fact of nonequivalence of forward and reversed processes in quantum physics is the conclusion about the existence of a certain memory of the quantum

system about its initial state. Without such memory, the quantum system will not be able to distinguish a forward process from a reversed one.

Such memory looks like as a physical equivalent of the concepts of entanglement, superposition of states, entropy. The probability of a complex quantum system (gas in a room) to return exactly into the initial quantum state is extremely small. Memory, like entropy, under such conditions can only to accumulate.

There are interesting and important questions: what is the carrier of this memory and where is it stored? Whether the memory is local or nonlocal?

It is difficult to believe that a lot of information can be written on an atom or a photon flying in a vacuum. In addition, to mark the position of the atom in space, there must exist some interaction between the atom and space. But we have here only a vacuum. However, today there is a general consensus that vacuum is not empty. Quantum fields, dark matter or dark energy exist here [60, 61]. Such vacuum is much better suited for recording memory. It can be assumed that the memory of a quantum system (as a physical equivalent of entropy) is recorded and stored in a vacuum. This hypothesis suggests an intriguing consequence [62].

Biologists today believe that our memory is stored in the brain, in neurons. However, the brain and neurons can be only the tool (as a grand piano) for extraction and reading the memory. But the memory itself (like a sheet music) is recorded and stored also in the physical environment. In this case we have a simple and natural explanation of the phenomenon of psychics, extra senses. There are people who have a special, supersensitive brain. It allows them not only to extract their own memories from the environment, but also to receive information about images and events which have no relation to them. Moreover, they can extract this information partly in quite non local way.

Young's double-slit interference is one of the most fundamental effects in quantum physics. Different theoretical models well describe this phenomenon, but its physical explanation is unclear till now. Feynman wrote: "We choose to examine a phenomenon which is impossible, *absolutely* impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the *only* mystery. We cannot make the mystery go away by "explaining" how it works" [63].

The situation looks like as when the photon (electron, neutron, atom) passes through one slit, it "knows" about the existence of the other slit. A similar situation exists in the Mach-Zehnder interferometer. When the photon reaches the second beam splitter (and "interferes with itself"), it "knows" about the existence of two ways in the interferometer. This corresponds to the idea of the existence of some "nonlocal knowledge" about the state of the macroquantum system.

This point of view is known as the conspiracy theory [64]. It looks like a supernatural, impossible physical explanation. But, probably, this explanation is the only true one. And the concept of non-local quantum memory supports such explanation [65, 66].

It should be noted that the superposition of quantum states and entanglement are more mathematical than physical concepts. It is usually said that the entanglement is the essence of quantum mechanics. The physical sense of this term is unclear. Maybe somewhere there is a mathematical definition of this term. But physical definition of the term "entanglement" is absent till now. However, now we can give physical definition to this term. *Entanglement is a memory of quantum system about its initial state, which manifests itself through inequality of differential cross-sections of forward and reversed processes.*

What to study

So, we do not have today the opportunity to experimentally study the dark matter. We have limited and questionable opportunities for studying the physical mechanism of brain functioning and the nature of our memory. However, we have an excellent opportunity of experimental studying of some properties of quantum memory by measurement of the difference between the differential cross-sections of forward, reversed and partially reversed quantum transitions.

Bloch oscillations of cold atoms in a vertical optical lattice are the best object today for such experimental study. It is the cleanest sample of a fully reversed quantum transition. We can experimentally study the dependence of its differential cross-section on the direction, frequency, phase of laser radiation, the position of atoms in space. During the time of free fall of the atom we can transfer it to another quantum states, to return it back and so on. In all these cases we shall observe a change in the probability of preservation of the Bloch oscillations. Such results can give the information about whether the memory of the quantum system about its initial state is preserved or degraded.

In general, experimental study of differential cross-sections of forward and reversed quantum processes is not a very difficult task. However, for many years I cannot convince our experimenters to begin such work. Till now there are no any directed experiments of this kind.

Conclusion

So, today we have more than enough direct and indirect experimental evidence of the nonequivalence of forward and reversed processes in quantum physics. **The discussed direct and indirect experimental evidence clearly show that the laws in quantum physics are not**

symmetrical in time. Nonequivalence of forward and reversed processes in quantum physics is the real physical base of nonlinear optics. The main consequence of this nonequivalence is the conclusion about the existence of a memory of the quantum system about its initial state. We can experimentally study this memory by measuring the differential cross-sections of forward, reversed and partially reversed quantum transitions.

The task of an experimental study of the time reversal noninvariance in quantum physics today is not so much a physical as a social problem. Experimenters are afraid to work in this direction. But we believe that sooner or later the situation here will move from the dead point.

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