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Creating nonlocal quantum entanglement between solid state devices with quantum optical control schemes

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Abstract

Current paper based on literature study is focused on analysis what solid state device is the most promising for practical realization and study of nonlocal entanglement. The main goal in experimental nonlocal entanglement realization is creation of qubits with long coherence times that can be manipulated and coupled together on a large scale. We will discuss various techniques and material systems that can be used for realization of nonlocal quantum entanglement and which of them are the most promising. Also in this paper the author will look into the future and predict feasible directions of development of this very interesting scientific direction.

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Introduction

Speaking about one of the strangest consequences of quantum mechanics we can say that probably entanglement is the most separate aspect of quantum theory. It plays a main role in the most interesting applications of quantum computation [1].To better learn qualities of entanglement researchers have made a great work but they have only found signs of entanglement between tiny particles such as ions, atoms and photons. Let's test quantum mechanics on a large scale. For example a good quantum computer is a long way off and the quantum world to classical world crossover is not clear. We still need to find a way to make entangled between solid state to use it in modern microelectronics. During many years of researching physicists were afraid of the violation of the rule of special relativity that information cannot travel faster than the speed of light. In fact in 1935, Albert Einstein, in collaboration with Boris Podolsky and Nathan Rosen, hoped to disprove nonlocal quantum mechanics by publishing a famous thought experiment describing what is now called "the EPR paradox" [2]. The most simple example of this paradox, two particles, A and B, are entangled in a spin singlet, $|\psi_{AB}\rangle = \frac{1}{\sqrt{2}}[|\uparrow\rangle_A|\downarrow\rangle_B - |\downarrow\rangle_A|\uparrow\rangle_B]$, where $|\uparrow\rangle$ and $|\downarrow\rangle$ refer to spin up and spin down, respectively. If the singlet is separated into two noninteracting particles, any subsequent measurement of the spin of particle A (e.g., found to be up spin) should immediately identify the state of particle B (e.g., required to be down spin) [3] where the logical qubit states are formed from entangled states between the electron and nuclear spins. Generally speaking in quantum information science a bit of information is called qubit. The qubit is a single-particle state in two-dimensional Hilbert space and can have two possible values $|0\rangle$ or $|1\rangle$ also qbit can be linear superposition of both values. In practice if the particle is a photon, qbit can be realized in few ways. First of all in polarization encoding, for example the logical state $|0\rangle$ can be correspond to left-circularly polarization of photon while state $|1\rangle$ to right-circularly polarization. If we have deal with solid and particularly with electron spin, $|0\rangle$ state may correspond to the spin $|\uparrow\rangle$ and state $|1\rangle$ to $|\downarrow\rangle$. In a present paper the most interest solutions will be described, they include: quantum dots, semiconductor optical microcavities, impurities in semiconductors, nitrogen vacancy(NV) centers in diamond, electron ensembles GaAs/AlxGa1-xAs structures. One of the most important purposes of this work is to define what are the most robust ways to the realization of the real scheme for preparing non-local entanglement between quantum states with solid state devices and predict in which way this interest branch of physics will go. Atom-photon entanglement was not evident in many previous experimental systems, from early measurements of Bell inequality violations in atomic cascade systems to fluorescence studies in trapped atomic ions. A prime example of current interest is strongly coupled cavity quantum electrodynamics, where individual atoms interact with photons in single-mode cavities[4]. In Section 2 we will discuss briefly about entanglement of physical principal and using QED cavity in entanglement generation process. Also we will discuss about entanglement and single q-dot in cavity[9-13] and about interest structure - Nitrogen Vacancy (NV) center in diamond [38] which allows obtain entanglement in ambient conditions. One of the most popular and efficient way of this realization is using three-level systems and DLCZ scheme[5] , because we are able to couple optical fields to low –energy spins with long-lived quantum coherence, in turn quantum coherence together with a classical driving field make that the three-level systems become a strongly modified optical medium . This fact can be used to prepare and detect particular spin wave states and give access to studies of nonlocal entanglement with many particle systems. In Section 3 we will consider the preparation of the entanglement between ensembles of atoms using DLCZ scheme. Further for preparing nonlocal entanglement with solid state devices .Also in Subsection 3, we will consider a quantum wells in GaAs heterostructure material as a new medium for entanglement, that is suited for realizing such an ensemble of three-level quantum systems and used the same approach of optical control scheme [6]. In Section 4 and Section 5 we will summarize all that was stated and will predict further perspective ways, practical realizations and applications of this field. Finally, we will try to answer to the question – what are the most robust systems and materials for entanglement realization.

1.1. Basic physical principle of entanglement

Entanglement is a property of a system which consist of two or more objects in which the quantum states of the these objects are linked together. That's why so one system can no longer be sufficiently described without full mention of its counterpart, even through her individual parts are spatially separated. [1, 2]. So, the basic concept is: if for instance we have a pair of particles and the have a two-state spin and one must be spin up and the other must be spin down, these two particles can now be called entangled since if it is impossible to fully describe one particle without mentioning the other. This type of entangled pair where the particles always have opposite spin is known as the spin anti-correlated case, and if the probabilities for measuring each spin are equal, you have the singlet state (1). For example, assume that we have eigenstate $|\psi\rangle_A = |0\rangle_A + |1\rangle_A$ of system A and eigenstate $|\psi\rangle_B = |0\rangle_B + |1\rangle_B$ of system B, the following state is an entangled:

$$|\psi\rangle_{AB} = \frac{1}{\sqrt{2}}[|0\rangle_A|1\rangle_B - |1\rangle_A|0\rangle_B] \quad (1)$$

So if the system is in this state, it is completely impossible to distinguish either of the system *A* or system B and definite pure state. In exchange for, their states are superposed and it means that these systems are "entangled". Now let's imagine that Alice is a viewer for system A, and Bob is a viewer for system B. If Alice makes a measurement in the $\{0\rangle, 1\rangle\}$ eigenbasis of system A, there are two possible outcomes and their probabilities of occurring are equal:

First case: If Alice will measure 0, the state of the system fall down to $|0\rangle_A|1\rangle_B$.

Second case: If Alice will measures 1, the state of the system fall down to $|1\rangle_A|0\rangle_B$.

If the former occurs, then any occurring after measurement performed by Bob, in the same basis, will always return 1. If the latter occurs, Alice measures 1 then Bob's measurement will return 0 with certainty. Thus, system *B* has been altered by Alice performing a local measurement on system *A*. It should note that the outcome of Alice's measurement is random. Alice cannot decide which state to

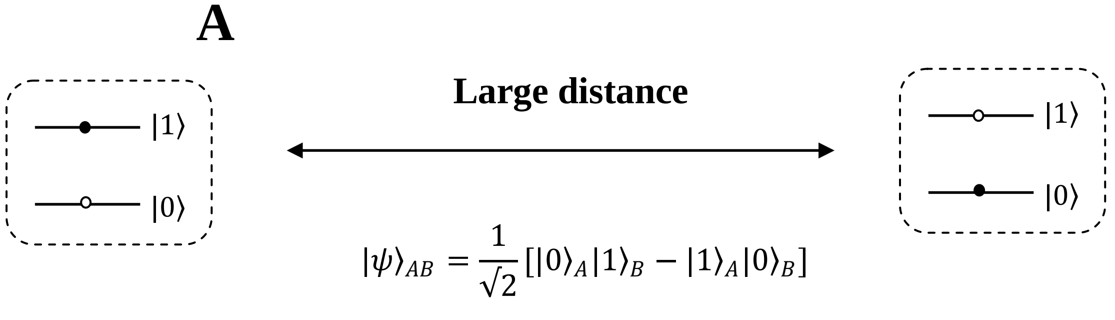

Fig.1. Scheme of the Nonlocal entangled states

collapse the composite system into, and therefore cannot transmit information to Bob by acting on her system. Causality is thus preserved, in this particular scheme Fig.1

1.2 Basic principle of entanglement generation scheme.

As was mentioned before there are several case to realize qbit in quantum information science so that's way it is obvious that possible to realize several types of entanglement. First of all it is entanglement spin and light and good example is quantum entangled states between a optical pulse and the electronic spin:

$$|\psi\rangle_{SPIN-LIGHT} = c_0 \mid \uparrow\rangle |0_{\mathrm{pulse}}\rangle + c_1 | \downarrow\rangle |1_{\mathrm{pulse}}\rangle \qquad (2)$$

where $|0_{\mathrm{pulse}}\rangle$ and $|1_{\mathrm{pulse}}\rangle$ are states with 0 and 1 photon states(absence or detecting photon), $\mid \uparrow\rangle$ and $\mid \downarrow\rangle$ are spin states of the system.

The possible alternative ways can be entangled states between a single photon and the electronic spin:

$$|\psi\rangle_{SPIN-LIGHT} = c_0 \mid \uparrow\rangle\, |\sigma_-\rangle + c_1 | \downarrow\rangle |\sigma_+\rangle \qquad (3)$$

where $|\sigma_+\rangle$ and $|\sigma_-\rangle$ are orthogonal circularly polarized single photon states and

$$|\psi\rangle_{SPIN-LIGHT} = c_0 \mid \uparrow\rangle\, |\upsilon_\uparrow\rangle + c_1 \mid \downarrow\rangle |\upsilon_\downarrow\rangle \qquad (4)$$

where $|\upsilon_\downarrow\rangle$ and $|\upsilon_\uparrow\rangle$ are two resolved frequencies.

The main goal is realize and observation entanglement between two remotely located system using the entanglement between light and atoms. So the final goal is obtaining two spins states entanglement of two separate system (Fig.1)

$$|\psi\rangle_{AB} = c_0 \mid \uparrow\rangle_A \mid \downarrow\rangle_B + c_1 \mid \downarrow\rangle_A | \uparrow\rangle_B \quad (5)$$

At the Fig.2 you can see scheme of experiment . It consists of two optical system 1 and 2, each may containing (a single trapped Λ three level atom in cavity [7,8] or without it (Fig.3a) or atomic ensembles of Λ three level atoms and also individual NV centers which incidentally have the similar Λ -type level system) .The photons flow out from both of the systems impinge on the 50/50 beam splitter BS and are detected at the single photon counters D_1 and D_2. Initially, we assume unit efficiency detectors (we include finite efficiency later).

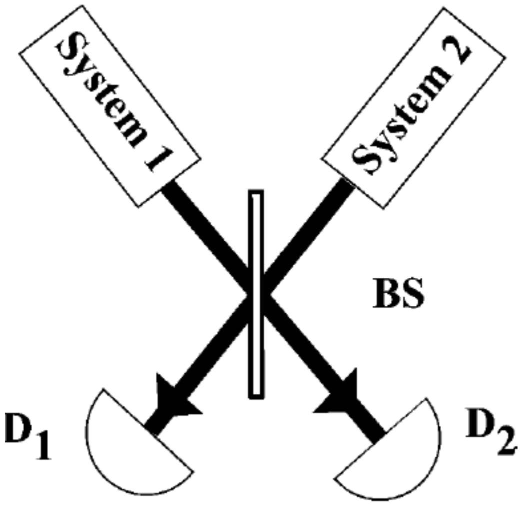

Fig.2. Two optical systems and two detectors coupled by a beam splitter (BS).Should note that this scheme common for experiments with single atom, single atom without cavity and for atom ensembles and also for NV centers .In section 2 this scheme will be discussed in detail.

Now we will discuss general idea. Assume we have two equal optical systems A and B as was mentioned above and in each system was realized quantum entangled states between a optical pulse and the electronic spin (2). So it is well known fact that quantum state of these two noninteracting systems A and B is possible write as tensor product. If the first system is in state $|\psi\rangle_A$ and the second in state $|\psi\rangle_B$, the state of the composite system is

$$|\psi\rangle_A \otimes |\psi\rangle_B \qquad (6)$$

The quantum state of the system before the photons interact on the 50/50 beam splitter is:

$$\left[\left(|\uparrow\rangle_\mathrm{A}|0_\mathrm{pulse}\rangle_\mathrm{A} + |\downarrow\rangle_\mathrm{A}|1_\mathrm{pulse}\rangle_\mathrm{A}\right) \otimes \left(|\uparrow\rangle_\mathrm{B}|0_\mathrm{pulse}\rangle_\mathrm{B} + |\downarrow\rangle_\mathrm{B}|1_\mathrm{pulse}\rangle_\mathrm{B}\right)\right] =$$

$$[\, |\uparrow\rangle_\mathrm{A}|0_\mathrm{pulse}\rangle_\mathrm{A} |\uparrow\rangle_\mathrm{B}|0_\mathrm{pulse}\rangle_\mathrm{B} + |\downarrow\rangle_\mathrm{A}|1_\mathrm{pulse}\rangle_\mathrm{A} |\uparrow\rangle_\mathrm{B}|0_\mathrm{pulse}\rangle_\mathrm{B} +$$

$$|\uparrow\rangle_\mathrm{A}|0_\mathrm{pulse}\rangle_\mathrm{A} |\downarrow\rangle_\mathrm{B}|1_\mathrm{pulse}\rangle_\mathrm{B} + |\downarrow\rangle_\mathrm{A}|1_\mathrm{pulse}\rangle_\mathrm{A} |\downarrow\rangle_\mathrm{B}|1_\mathrm{pulse}\rangle_\mathrm{B}]=$$

$$\frac{1}{2}(|\Phi^+\rangle_a|\Phi^+\rangle_p + |\Phi^-\rangle_a|\Phi^-\rangle_p + |\Psi^+\rangle_a|\Psi^+\rangle_p + |\Psi^-\rangle_a|\Psi^-\rangle_p) \qquad (7)$$

Where $|\Phi^\pm\rangle_a = (|\uparrow\rangle_\mathrm{A} |\uparrow\rangle_\mathrm{B} \pm |\downarrow\rangle_\mathrm{A} |\downarrow\rangle_\mathrm{B})$, $|\Psi^\pm\rangle_a$=$(|\uparrow\rangle_\mathrm{A} |\downarrow\rangle_\mathrm{B} \pm |\downarrow\rangle_\mathrm{A} |\uparrow\rangle_\mathrm{B})$ are the maximally entangled Bell States for atoms. When the photon matched on the 50/50 beam splitter the photons exit on different ports only if there are in antisymmetric state [26]

$$|\Psi^-\rangle_p=(|0_\mathrm{pulse}\rangle_\mathrm{A} |1_\mathrm{pulse}\rangle_\mathrm{B} - |1_\mathrm{pulse}\rangle_\mathrm{A} |0_\mathrm{pulse}\rangle_\mathrm{B}) \qquad (8)$$

Therefore, the main idea that in such configuration a detector click implies that one quantum of spin has been created in two systems, but it is fundamentally impossible to determine from which of two systems the photon arrived. In this case the measurement projects the state of the system into an maximally entangled state of two systems.

$$|\Psi^\pm\rangle_a=(|\uparrow\rangle_\mathrm{A} |\downarrow\rangle_\mathrm{B} \pm |\downarrow\rangle_\mathrm{A} |\uparrow\rangle_\mathrm{B}) \qquad (9)$$

First of all our working media need to have a long coherence time, because we require both systems to be one sided so that the only leakage of photons occurs through the sides of the cavities facing BS. Also this have to prove strong interactions with photons, for example, a medium with high optical density or a medium inside a high finesse optical cavity. A good point to use atoms trapped in cavities (Fig.3b.) [7,8] but it is necessary to say that using optical cavities is technically demanding. In the next section we will discuss experiments with single atom using cavity QED, single atom without cavity and for atom ensembles, D^0-D^0X system in n-GaAs structures and also for NV centers.

We should say that in this work the basic principle of preparation step is always the same, for all experiments that was discussed here, we use three-level system (or sometimes it's called Λ −system).

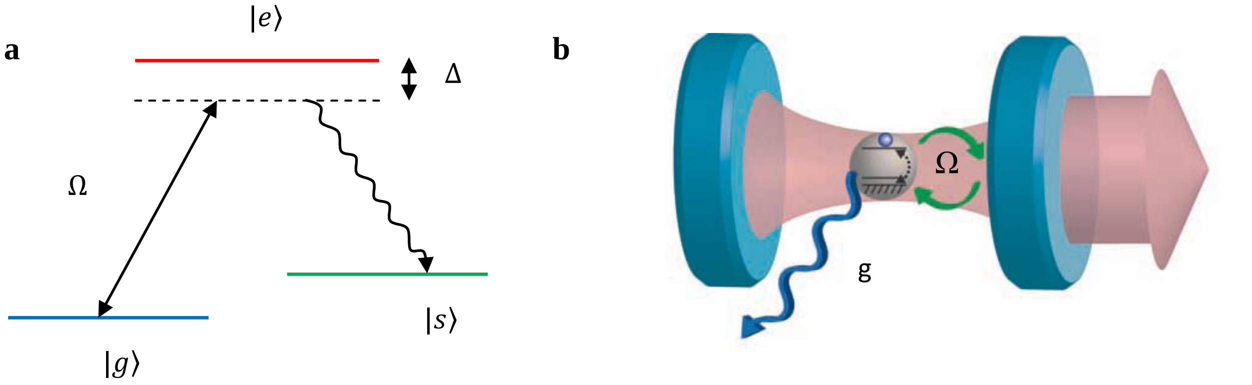

Fig. 3.

- **a)** The Λ three - level configuration of the trapped atom are shown. The $|g\rangle \rightarrow |e\rangle$ transition being driven by a classical laser field with the Rabi frequency Ω and the forward-scattered Stokes light from the transition $|e\rangle \rightarrow |s\rangle$ and this transition being driven by the quantized cavity mode. Δ is the detuning of both the classical laser field and the quantized field mode from their respective transitions.
- **b)** Shown is a simple schematic of an atom–cavity system depicting in cavity QED, where $\Omega \approx g$ (Ω is the one-photon Rabi frequency , coherent coupling g). Coherent exchange of excitation between the atom and the cavity field proceeds at rate g, as indicated by the dashed arrow for the atom and the green arrows for the cavity field.

The three level atoms have two ground states $|g\rangle$ and $|s\rangle$ (for instance Zeeman sublevels) and an excited state $|e\rangle$ are shown in Fig. 3a. Alice and Bob use two types of time evolutions of the atom cavity system as their basic local operations. The first type is initiated by switching on a classical laser field which drives the $|g\rangle \rightarrow |e\rangle$ transition with a coupling Ω (Rabi frequency).
The $|e\rangle \rightarrow |s\rangle$ transition is driven by the quantized cavity mode of coupling g. Both the classical laser field and the cavity modes are assumed to be detuned from their respective transitions by the same amount Δ. Meanwhile this scheme will work for N atoms as well. So it means that this Λ three - level configuration is suitable for atom ensembles structures.

Section 2. Experimental Demonstrations

2.1 Preparation of nonlocal entanglement using single atoms

In this chapter we consider two remotely trapped atoms, as example trapped Rb^{87} atom and we will see possible possible realization of the generation and characterization of entanglement between the spin of a single trapped Rb^{87} atom and the polarization of a photon at a wavelength of 780 nm and as consequence realization of entanglement of two remote qubits. Entanglement between the internal atomic state and the polarization of the photon is generated in spontaneous decay in a Λ - type transition. For these purposes our of our experiment we have to satisfy the following criteria:

- First of all, presence of stable ground states which are suitable for encoding a qubit and which have preferably a simple structure.
- Our atom should have qubit states which form a Λ -type system with an excited state for the generation of entanglement.
- The optical transitions for cooling, preparation have to be accessible with present laser Technology.

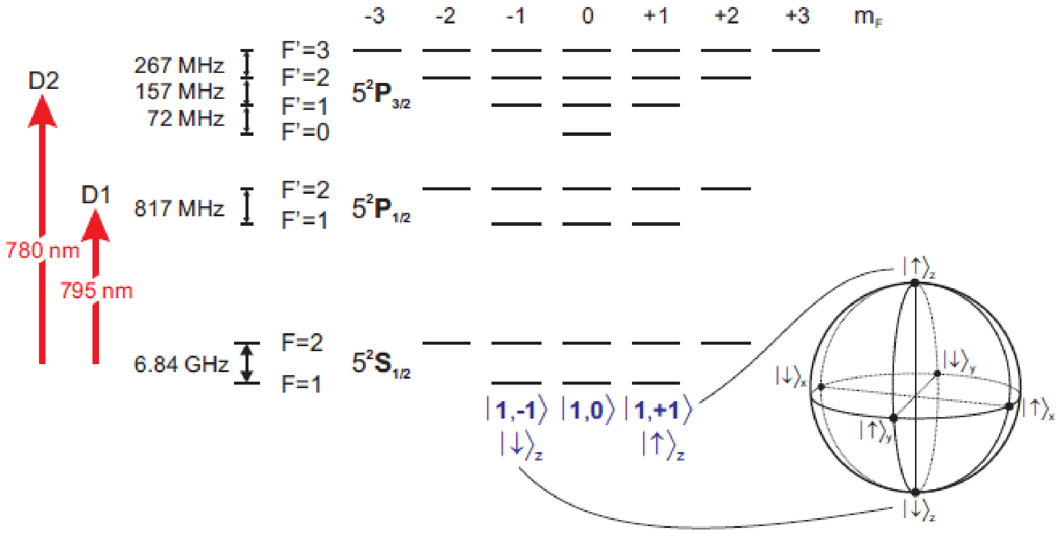

Fig. 4.
Energy levels of Rb^{87}. Ground level $5^2S_{1/2}$ and the first two exited levels $^{2S1}/2$ and the first two exited levels $5^2P_{1/2}$ and $5^2P_{3/2}$ with their respective splitting are shown. The qubit is encoded in the |F = 1,mF = ±1i states of the ground level. Also the Bloch sphere represents atomic qubit states. Picture from [49].

Alkaline metal is very promising element for criteria that mentioned above. So element Rb^{87}, which is an alkaline metal with a single outer electron. It has a nuclear spin $I = 3/2$ leading to the ground state $5^2S_{1/2}$ with a hyperfine splitting in F=1 and $F = 2$ (see Fig. 4). The $F = 1$ and $F = 2$ hyperfine levels consist of 3 and 5 Zeeman substates respectively. The first exited state is split because of the interactions of $5^2P_{1/2}$ and $5^2P_{3/2}$ states with their corresponding hyperfine and Zeeman structure. For the ground hyperfine substates , for convenience, we will use the symbol $|F, m_F\rangle$ and for excited states $|F', m_F{}'\rangle$.The optical dipole transitions from the ground state into exited states $5^2P_{1/2}$ and $5^2P_{3/2}$ are called the D1(780 nm) and the D2(795 nm) transitions, respectively. Our qubit is encoded as the two long lived Zeeman states $|F = 1, m_F = -1\rangle$ and $|F = 1, m_F = +1\rangle$, which are degenerate when magnetic field is absent. And these states correspond to the combined atomic spin $|\uparrow\rangle$ and $|\downarrow\rangle$ and they together with a selected state $5^2P_{3/2}\ |F' = 0, m_F{}' = 0\rangle$ form a Λ – type system, as was mentioned previously is a crucial point for the the generation of atom-photon entanglement.

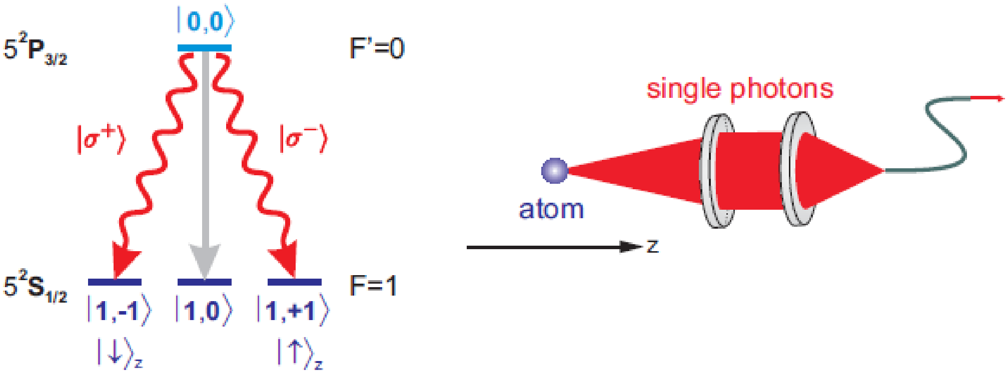

Fig. 5. Principle of atom-photon entanglement. The exited atomic state $|F' = 0, m_F{}' = 0\rangle$ has three possible optical decay channels. The polarization of the emitted photon is entangled with the final state of the atom. Coupling the emitted light into a single-mode fiber suppresses the collection of photons from the π -decay. The common optical axis of the objective and of the optical fiber define the quantization axis z. Picture from [49].

The principle of atom-photon entanglement is the same as was described in paragraph 1.2. In this case atom photon entanglement is generated in the spontaneous decay exited atomic state(see Fig. 5) from the state $5^2P_{3/2}\ |F' = 0, m_F{}' = 0\rangle$ (lifetime 26 ns) .Atom will decay optically into the state F=1, decay into two states $|F = 1, m_F = -1\rangle$ and $|F = 1, m_F = +1\rangle$ which leads to emission of σ_+ or σ_+ photons (left or right circularly polarized respectively) while transition to the state $|F = 1, m_F = 0\rangle$ correspond to π -polarization emitting photon(due to the law of conservation of angular momentum), expectation value of π -photon equal to zero. As far as the system of the atom together with the emitted photon is closed, the emission process is coherent. In particular the total system after the emission is in a pure state (the same as formula (3) in section 1.2):

$$|\psi\rangle_{\mathrm{SPIN-LIGHT}} = \frac{1}{\sqrt{2}}(|1,-1\rangle|\sigma_+\rangle + |1,+1\rangle|\sigma_-\rangle) \qquad (10)$$

The restriction of the two decay channels leads to the generation of a perfectly entangled state between the atomic qubit encoded in the spin and the polarization of the photon. Also it is necessary to say that this generation process is probabilistic because the spontaneous emission is not directed.

It is very important to say about state selectivity problem. Actually method which is called STIRAP(stimulated Raman adiabatic passage) are very efficient method for separate of the hyperfine levels F = 1 and F = 2, and that's why it helps to remain problem is to distinguish between arbitrary superpositions in the qubit subspace { $|1,-1\rangle$, $|1,+1\rangle$ } . Particularly what is needed that transfers a selected superposition to the F = 2 level shouldn't affect to the other one.

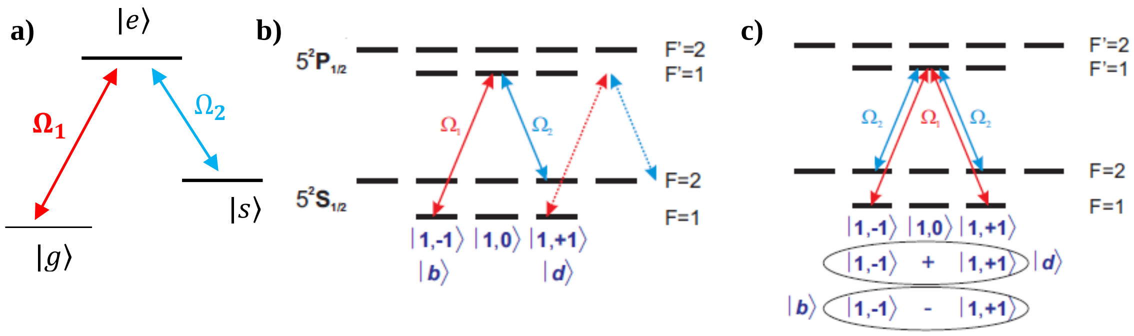

Fig. 6. Illustration of STIRAP Principle.

- **a)** The initial state $|g\rangle$ and the final state $|s\rangle$ are coupled to an excited state $|e\rangle$ by two fields with Rabi frequencies Ω_1 (historically called pump) and Ω_2 (Stokes).
- **b)** State selectivity of the STIRAP process for the cases of circular polarization of the STIRAP light.
- **c)** (Linear polarization). For each polarization of the applied STIRAP light there exist a bright state $|b\rangle$, which is transferred, and a dark state $|d\rangle$, whose transfer is forbidden. Picture from [49].

STIRAP is a efficient method for transfer of population between two states. At the Fig. 6.(a). Λ –type system depicted with two ground states $|g\rangle, |s\rangle$ and one exited state $|e\rangle$. These levels are coupled resonantly by two light fields STIRAP$_1$ and STIRAP$_2$ with respective Rabi frequencies Ω_1 and Ω_2. In order to select the measurement basis of our qubit Fig 6 (b),(c) the transferring process has to distinguish between superpositions of states in the { $|1,-1\rangle$, $|1,+1\rangle$ } space. This can be achieved by using selection rules of atomic transitions. Any polarization of the STIRAP$_1$ light field can be expressed as a superposition of σ+ and σ− polarization. There exists a superposition of $|1,-1\rangle$ and $|1,+1\rangle$ states which couples to this field, this state is called a bright state $|b\rangle$ The orthogonal superposition does not couple to the field and is called a dark state $|d\rangle$. Under these conditions the bright state $|b\rangle$ will evolve as described in the previous section (i.e. it will be transferred) while the dark state $|d\rangle$ ideally stays unchanged. The next problem for this experiment is creation a trap for single neutral atoms. For the experimental realization of atom-photon entanglement, as well as for any experiment with a single atom, the first requirement is to trap and to isolate a single atom. Furthermore the atom has to be accessible for manipulation and detection. The trap has to provide sufficient holding time and to preserve the internal atomic state. The possible candidates for trapping of single atoms are magnetooptical trap (MOT), magnetic trap and optical dipole trap. The MOT relies on forces resulting from scattering of light, and therefore does not preserve the internal state. The magnetic trap is state dependent - it uses magnetic polarization of the atom, so it can not trap both of the Zeeman states which constitute the qubit. The only available trapping principle which is capable to fulfill our requirementsis based on the optical dipole force. The progress entanglement observation between a single trapped atom and a single photon was reported [44]. In this experiment was shown a effective fidelity of this experiment F=0,87 ±0,01.Now we will think about towards the verification of the entanglement between the two distant atoms. As we told above to realize the remote entanglement of atomic qubits we need realize two basic principles: atom-photon entanglement, and quantum state transfer from an atomic to a photonic qubit. Lets estimate what parameters should we have to transfer of atom-photon entanglement into remote atomic qubit entanglement. So the two photons are brought together and serves to swap the entanglement to the atoms[45**]**. If we use the average fidelity observed in experiment [45] and extrapolate results of recent two-photon interference experiments

[46], we derive an expected atom-atom fifelity of $F_{at\text{-}at}=F_{at\text{-}ph}^2$. The next it is possible to make estimation what the minimum distance of the atoms should be, it is clear that it determined by the duration of the atomic state detection. In generally, the atomic state collapses by scattering photons from the detection laser for 350 ns. Together with the STIRAP process, this yields an overall measurement time of less than 0,5 μs and requires a separation of the atoms of 150 m. Thereby, it is possible to expect the generation of one entangled atom-atom pair per minute, because the atomic state detection has to be performed only when a photon pair event is registered, the repetition rate will be significantly higher than expected from the square of the success probability of atom-photon generation , by 3 standard deviations would require approximately 7000 atom pairs at the expected fidelity of 0.74. So we are able to detect our generation of entanglement within a total measurement time of 12 days actually it is not that what we are expecting!

Actually it is possible to combined this experiment with high-*Q* cavities to enhance the collection efficiency .One of the best realization of entanglement of two fixed single-atom which was separated by one meter was proposed in work [48] .The scheme was identical but instead Rb was used ions of a rare earth element Yb. In each of two congeneric radio-frequency ion traps was a single ${}^{171}Yb^+$ ion.

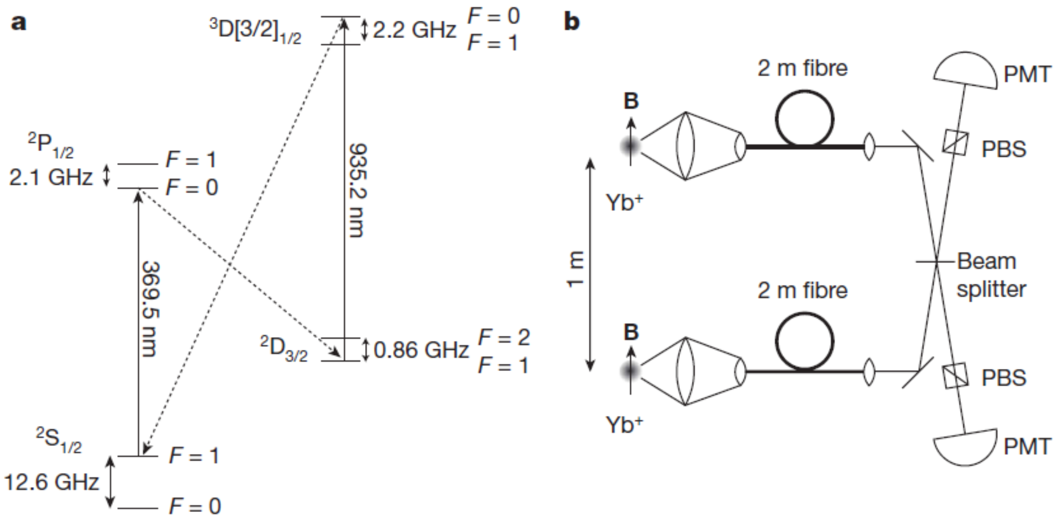

Fig. 7. a) Correspond energy levels for ${}_{171}Yb^+$. The ${}^2S_{1/2}{}^2P_{1/2}$ transition is driven by light at 369.5 nm. When system excited to ${}^2P_{1/2}$, the ion can decay to the ${}^2D_{3/2}$ .A diode laser at 935.2nm pumps the ion out of this state through the ${}^3D[3/2]_{1/2}$.**b)** Two ions are trapped in independent vacuum chambers separated by approximately 1 m. Spontaneously emitted photons from each ion further are coupled into single mode fibres. The polarization of each photon is defined with respect to the applied magnetic field B oriented perpendicularly to the collection direction. The output of each fibre is spatially mode-matched on a 50/50 non-polarizing beam splitter leading to an interference contrast of greater than 97%. Picture from [48].

It is necessary to say that with an experiment[48] repetition rate was $R=5.5x10^5\ s^{-1}$, this fact guarantees that entanglement event can be detected approximately every 8.5 min.

2.2. Preparation of nonlocal entanglement using QED cavity

Cavity quantum electrodynamics (cavity QED) is the study of the interaction between light confined in a reflective cavity and atoms or other particles, under conditions where the quantum nature of light photons is significant. At the forefront of efforts to achieve strong, coherent interactions between light and matter has been the study of cavity QED [9]. Trapping of single atoms in high-*Q* cavities [10] opens up exciting possibilities for the observation and manipulation of the dynamics of single particles and for control of their interactions with single-mode photons [11, 12].The first experiment to achieve strong coupling in cavity QED with trapped atoms was that of [11], which reported trapping lifetimes of 28 ms. By now, this experiment has attained much longer trapping times, with recent work demonstrating lifetimes in excess of 1 s [12]. The 'strong coupling regime' of cavity QED is obtained when the rate of absorption or emission of a single photon by the atom is more rapid than any of the rates of loss $g >> \kappa,\gamma$ (where γ is the atomic decay rate to modes other than the cavity mode and κ is the decay rate of the cavity mode itself and $2g$ is the one-photon Rabi frequency). In this case, an excited atom in an initially empty cavity will emit one (and only one) photon, which can then be trapped and reabsorbed again (at rate $2g$), a phenomenon known as vacuum Rabi oscillations. The presence of the cavity has made the spontaneous emission from the atom, usually an irreversible process, into a coherent and reversible oscillation. In both the optical and the microwave domains, strong coupling of single atoms and photons has been achieved by using electromagnetic resonators of small mode volume with quality factors $Q \approx 10^4$. In the past three decades, a variety of approaches have been used to achieve strong coupling in cavity QED[13]. In the optical domain, aroute to strong coupling is the use of high-finesse optical resonators ($F \approx 10^5$–10^6)

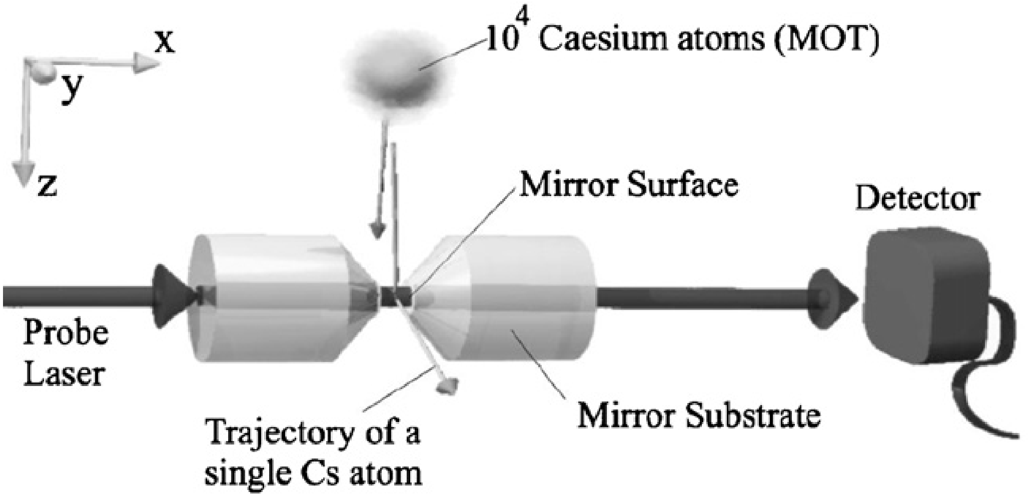

Fig.8. Schematic illustration of the atom–cavity microscope. Cold atoms are delivered to the cavity mode by releasing the contents of a magneto-optic trap (MOT) a few millimeters above the cavity. Fabry–Perot cavity, which is shown schematically. The cavity length l = 10 µm, waist w_0 = 12 µm transverse to the cavity axis, and finesse $F \approx 5 \times 10^5$. The supporting structure allows active servo control of the cavity length to $\delta l \approx 10^{-14}$ m . Facilitated atomic trapping times T = 0.5 ms.
Figure from [13].

Extensions of cavity QED to other systems[14] include quantum dots coupled to micropillars and photonic bandgap cavities[15, 16] and Cooper pairs interacting with superconducting resonators (that is, circuit QED [17]). And through its ability to use photons to communicate between several qubits, circuit QED may help to bring about more complex quantum systems with superconducting circuits. Semiconductor structures offer the unique capability of permanently positioning a QD in the middle of a nanocavity. The work of [15] describes the history of realizing vacuum Rabi splitting (VRS) in the single-QD.The great appeal of micro-QD and nanocavities is that they can be easily and monolithically fabricated, which in turn increases their suitability for large-scale integration into more-complex arrays and circuits. Almost every type of microcavity structure has been considered in the quest for SQD VRS, including micropillars, microdisks, photonic-crystal-slab nanocavities.
Fig. 5 summarizes the three recent experiments[18–20] demonstrating SQD VRS and
compares them with VRS due to a single trapped Cs atom.

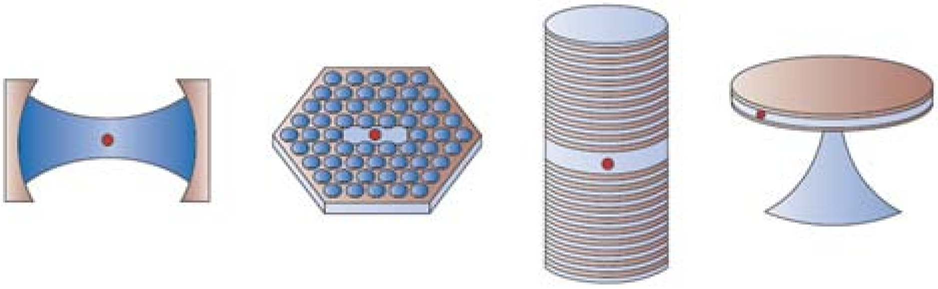

Fig. 5. This picture depicts comparison of systems exhibiting vacuum Rabi splitting using a single oscillator: a single trapped atom[21] or a single QD in a photonic-crystal-slab nanocavity[18], in a micropillar[19], or a microdisk[20]. Figure from [15].

One possible way to realize nonlocal entanglement with using quantum dot in cavity was described in [22]. In this work, was proposed and developed the theory of realization an integrated solid-state device that enables pronounced entanglement between macroscopically separated quantum dots on-chip. The Bell states was generated by a single photon source, where the single photons are first split by a 50%−50% beam splitter, and then undergo a different phase delay (0 or π), which then excited the pair of QDs. More elaborate schemes could, in principle, send in an incident field through a leaky waveguide mode, that could prepare the QDs pair in the correct superposition state.

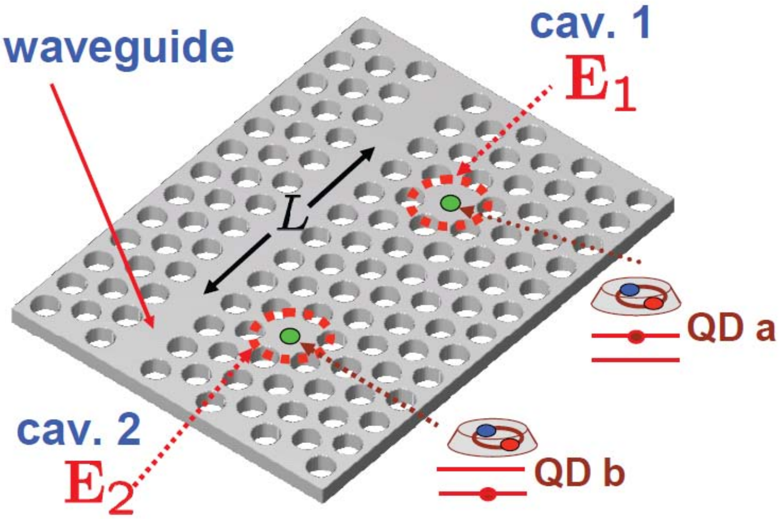

Fig. 6. Schematic diagram of system, which is composed of two cavities and one waveguide, with one quantum dot in each cavity. The distance between the two cavities is *L*, and as an example, was shown that q-dot *a* is initially excited and q-dot *b* is in the ground state. Picture added from [22]

Experimentally, the quantum dots are usually optically excited far off resonance, and the initial excitons are created incoherently. While the usual coupled-quantum dots entanglement distance between excitons is only about 10 nm, here we obtain a macroscopic entanglement by indirect cavity-cavity coupling, via the integrated waveguide. Furthermore, this macroscopic entanglement has the added advantage that the coupling phenomena can be probed by measuring the individual cavity-emitted light spectra . Cavity-QED coupling between two QDs in a single PC cavity [23] has also been shown to lead to sizable entanglements for QDs that are coupled nearby to the same cavity. For single QDs, at low temperatures of $T = 4$K, even for regular (non-cavity) structures, the exciton relaxation is typically dominated by radiative decay, and the non-radiative decay times, so this experiment demands He temperatures that without doubt is a huge drawback for industrial applications. One of the advantages of this experiment was fact that large for the large cavity separations, the vacuum Rabi oscillations are suppressed, and for L = 300 µm, a clear retardation feature of around 10 ps is observed. When L is increased to a larger value of 300 µm, the entanglement peak is still reasonable (~0.3). While the usual coupled-QD entanglement distance between excitons is only about 10 nm, here was shown a macroscopic entanglement by indirect cavity-cavity coupling, via the integrated waveguide. For our aim, it is very interesting experiments, because macroscopic entanglement is our goal, despite that fact that it was shown that nonlocal entanglement could be realize on scale 300 µm and only but entanglement dynamics will be robust for up to several hundred picoseconds but it shows that effective “QD molecules” can be formed over several hundred microns and using these systems to have a rich dot-cavity and dot-dot coupling dynamics. The coupled-cavity QED technique facilitates a way to test the violation of the Bell inequality and quantum entanglement by looking at the emitted light spectrum above each dot-cavity pair.

2.3. Nitrogen Vacancy (NV) center in diamond

First of all robust entanglement at room temperature is a necessary requirement for practical applications in quantum technology. Should note that the in most technique today phonons are one of the main sources of decoherence for solid-state quantum objects, and hence recent demonstrations of strong coherent coupling between optically active quantum systems have been done at low temperature, and today it is the biggest drawback. One of the exception to this general rule is the nitrogen-vacancy (NV) defect in diamond [35]. If add to this fact a long coherence time of electron spin we are able to create unique solid-state qubit which can be implanted in diamond and this system allows to get a good optical redout of single atom spin. The structure of the NV colour centre is shown in Fig. 7a. It consists of a nitrogen and a vacancy in an adjacent lattice site. Consider a system involving an NVelectron spin interacting with a single proximal ^{13}C nuclearspin (Fig. 7c).When the electron is in the $m_s = 0$ state, the hyperfine interaction vanishes. When the electron is in the $m_s = 1$ state, the hyperfine interaction introduces a splitting ω_1 between the nuclear spin states $\{|1,\downarrow\rangle, |1,\uparrow\rangle\}$. Therefore we can selectively flip the electron spin state conditional on the nuclear spin. If we apply a weak magnetic field perpendicular to the nuclear spin quantizetion axis, the nuclear spin precesses at the Larmor frequency ω_l when the electron spin is in the $m_s = 0$ state. When the electron spin is in $m_s = 1$, the large hyperfine splitting ω_1 prevents Larmor precession. By selectively driving a pulse on one hyperfine transition $|0,\downarrow\rangle \leftrightarrow |1,\downarrow\rangle$, and then waiting for a time $\tau = \pi/\omega_l$, we can map a nuclear spin superposition onto the electron spin, $|0\rangle \otimes (\alpha|\downarrow\rangle + \beta|\uparrow\rangle) \rightarrow |\downarrow\rangle \otimes (\alpha|1\rangle + \beta|0\rangle)$. To investigate the degree of independent control over the two coupled qubits, authors studied the nuclear spin evolution under the optical excitation used to polarize and measure the electron spin qubit. A nuclear spin state $(|\uparrow\rangle + |\downarrow\rangle)/\sqrt{2}$ or $|\uparrow\rangle$ was prepared by initializing into $|\downarrow\rangle$ and allowing the spin to precess for either $\tau/2$ or τ. Finaly it was estimated the coherence properties in contrast to the electron spin, which dephases on a time scale $T_{2e*} \sim 1$ ms for this NV center, the nuclear spin free precession signal persisted out to ~0.5ms.

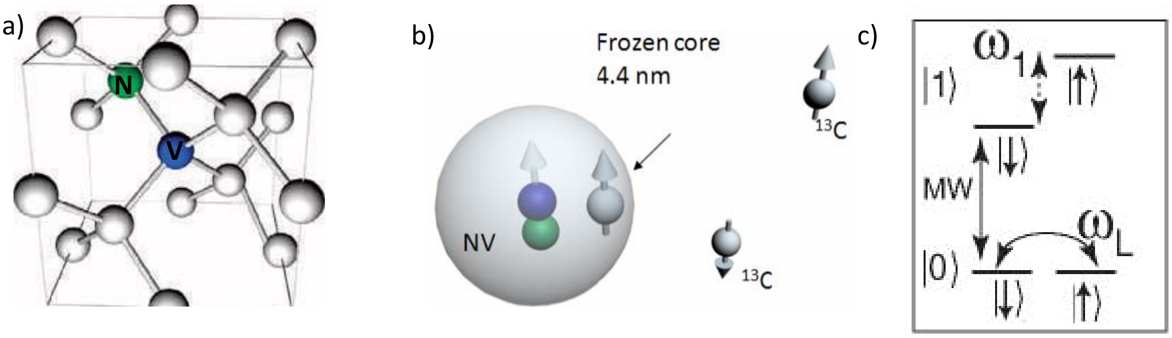

Fig. 7 **a)** The structure of the NV color centre is shown. It consists of a nitrogen and a vacancy in an adjacent lattice site. **b)** Schematic diagram of Dipolar coupling of NV spin with ^{13}C . **c)** Level diagram for the coupled spin system formed by the NV electron spin and a nearby 13C nuclear spin. A single electron spin transition $|0\rangle$ to $|1\rangle$ is addressed with resonant microwaves (MW), and hyperfine structure associated with the ^{13}C spin states $|\uparrow\rangle$, $|\downarrow\rangle$ can be resolved within this transition. Figure from [35].

Entanglement between an optical photon and a solid-state spin qubit was shown [36]. It was shown that nitrogen-vacancy (NV) is a promising candidate for realization of nonlocal entanglement in solid state devices. At this experiment was shown that the ground state of the negatively charged NV centre is an electronic spin triplet with a 2.88-GHz zero-field splitting between the magnetic sublevels $|m_s = 0\rangle$ and $|m_s = \pm1\rangle$ states with long coherence times near 1.8 ms at room temperature.

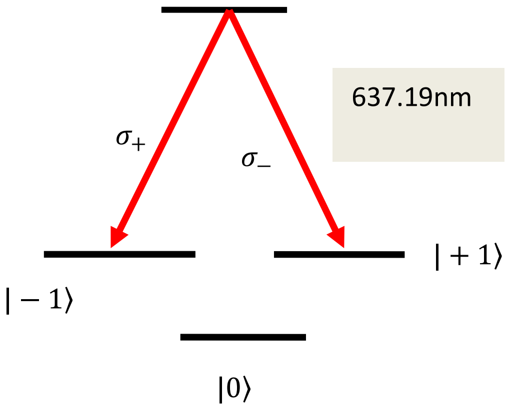

Figure 9. Scheme for spin-photon entanglement realization. Λ-type three level system decays to two different spin states through emission of orthogonally polarized photons, resulting in spin-photon entanglement.

It is necessary to say that the entanglement generation succeeds with probability $p \approx 10^{-6}$. We also could to estimate entanglement probability from of pairs of remote quantum registers. As this measurement can be done by coincidence measurements on a pair of photons emitted by two remote centres. So such entanglement generation over distance L is proportional to $p^2 \frac{\gamma T}{1+\gamma\tau}$, where $\gamma \approx 2\pi \times 15\,MHz$ is the spontaneous decay rate of the NV centre, $\tau = L/c$ is the photon travel time, c is the velocity of light and T is memory lifetime. For experiment realization spim memory time could be extended to hundreds of milliseconds using spin echo-techniques. For example by using a photonic crystal nanocavity the potential rate for spin-spin entanglement generation can be about 1MHz for $\tau < 1/\gamma$ and a few hertz for τ corresponding to $L \approx 100\,km$, resulting in $p^2 \frac{\gamma T}{1+\gamma\tau} \geq 1$. So we can claim that our ability to control interactions between NV centres and quantum light fields demonstrates that all-optical spin control, non-local entanglement can be implement using long-lived solid-state qubits.

2.4 . Entanglement with atomic ensembles

As was mentioned before the system that was described in section 2.2 will work for N atoms as well. So a realistic scheme for entanglement distribution by way of a quantum-repeater architecture was proposed by Duan, Lukin, Cirac and Zoller and is known as the DLCZ protocol [5]. The DLCZ protocol is based on ensembles of Na identical atoms (blue) with a Λ-level configuration, as shown in the figure (Fig.9.b.). The metastable lower states $|g\rangle$ and $|s\rangle$ can be, for example, atomic hyperfine states of the electronic ground level to ensure a long lifetime for coherence (Zeeman sublevels). All atoms are initially prepared in state $|g\rangle$ with no excitation.

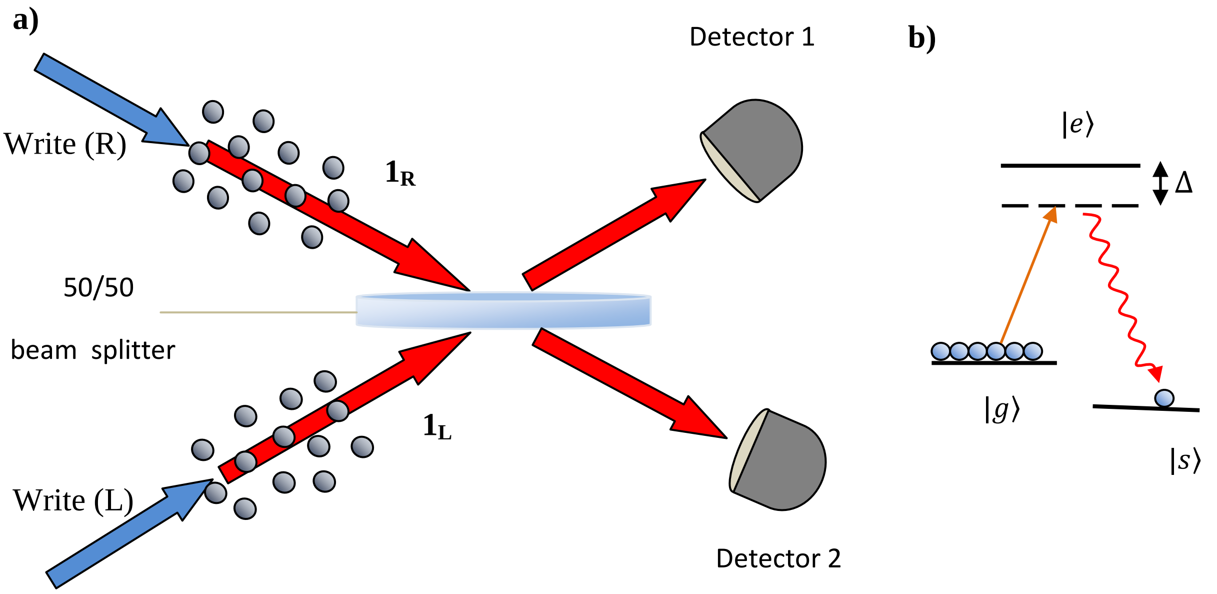

Fig.9. **a)**Scheme of measurement-induced entanglement between two atomic ensembles[5,24], L and R, is shown. **b)** The Λ three level configuration of the trapped atom are shown. Result is an entanglement state of two ensembles: after interference at BS it is impossible to determine where Stokes photon came from.

Long lifetimes for the relevant coherence have been observed both in a room-temperature dilute atomic gas [25, 26] and in a sample of cold trapped atoms [27]. To facilitate enhanced coupling to light, the atomic medium is preferably optically thick along one direction. This can be achieved either by working with a pencil-shaped atomic sample [25] or by placing the sample in a low-finesse ring cavity [28].Synchronized laser pulses incident on the ensembles (denoted write beams, blue arrows) generate small amplitudes for optical fields from spontaneous Raman scattering [29] these fields are denoted 1_L and 1_R (red arrows). These fields interfere at a 50/50 beam splitter, with outputs directed to two single-photon detectors. A measurement event at either detector (shown for detector 1) projects the ensembles into the entangled state $|\psi_{L,R}\rangle$ with one quantum of excitation shared remotely between the ensembles. The main advantage of this is method is that collective states store all quantum correlations and allow for readout via polaritons, directionality it has a good pulse shaping as long as spin coherence is preserved. For instance it is possible to make entanglement process ([5]; Fig. 8a) between two pencil-shaped ensembles L and R in terms of clouds of cold caesium atoms or rubidium. The atomic level structure for the writing process consists of the initial ground state $|g\rangle$ ($6S_{1/2}$, F= 4 level of atomic caesium), the ground state $|s\rangle$ for storing a collective spin flip ($6S_{1/2}$, F =3 level), and the excited level $|e\rangle$ ($6P_{3/2}$, F=4). The transition $|g\rangle \rightarrow |e\rangle$ in each ensemble coupled by a write pulse detuned from resonance to generate the forward-scattered anti-Stokes Field 1 from the transition $|e\rangle \rightarrow |s\rangle$.(Fig 9a) Schematic for check of entanglement between the L and R ensembles by conversion of atomic to field excitation by way of simultaneous read pulses obtained from BS described in Fig .9b.The read pulses reach the samples after a programmable delay from the write pulses, and couple the transition $|s\rangle \rightarrow |e\rangle$l ($|e\rangle$ being the 6P1/2, F=4 level), leading to the emission of the forward-scattered Stokes fields 2L and 2R from the transition $|e\rangle \rightarrow |g\rangle$.

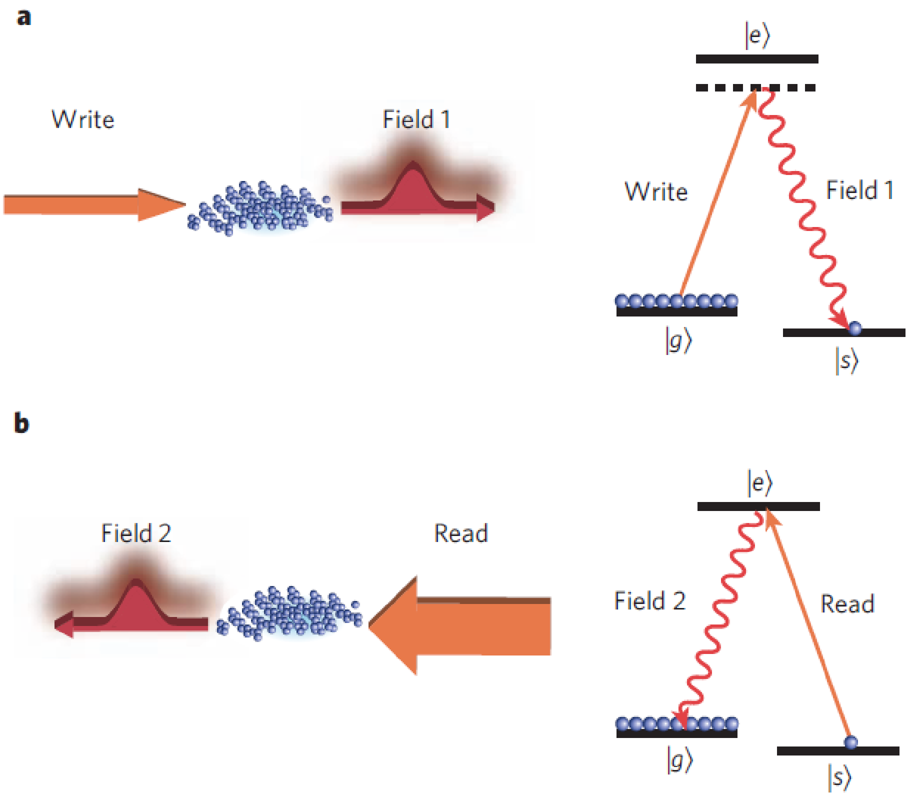

Fig. 10. Writing and reading process is the generation and retrieval of single 'spin' excitations within an ensemble of a large number of atoms .Picture from [50]

The entangled state is generated in a probabilistic but heralded manner from quantum interference in the measurement process. That is, detection of a photon from one atomic ensemble or the other in an indistinguishable manner results in an entangled state with one collective spin excitation shared coherently between the ensembles. In the ideal case, and to lowest-order probability, a photoelectric detection event at either of the two detectors projects the ensembles into the entangled state

$$|\psi_{L,R}\rangle = \frac{1}{\sqrt{2}}(|0_a\rangle_L|1_a\rangle_R \pm e^{i\varphi}|1_a\rangle_L|0_a\rangle_R)$$

with the sign (+ or–) determined by whether detector 1 or detector 2 records the event, phase φ determined by the difference between the phase shifts along the two channels phase shifts and can be derived from experimental conditions[5, 26, 30].

Limited by the coherence time between the metastable lower atomic states $|g\rangle$ and $|s\rangle$ for all atoms i = 1, 2, ... , *N*a within the ensemble Fig.9, this entangled state is stored in the quantum memory provided by the ensembles and is available 'on demand' for subsequent tasks, such as entanglement connection [5]. The one of the first experiment was made [34] in atomic Rb vapor at temperatures 70 - 90 C^0 .The technology is simple and relies on glass cells filled with atomic gas at room temperature. At present work the technology is limited to near infrared wavelength suitable for free space propagation and in this work was shown entanglement of atomic ensembles at a distance of half a meter with dephasing time of 0.5 ms. But the most interst realizations of this scheme, because it was made in solid, was made in Kuzmich group [36] and Kimble group[37] they used pencil-shaped ensembles using cold atomic clouds of ^{85}Rb and clouds of cold caesium atoms which was confined. But this experiments showed storage/retrieval efficiency ~ 2-11% and also $\Delta t_s \simeq 1$ μs for storing entanglement. Should mention that they used magneto-optical trap for atomic ensembles.

The long lifetime of this multi-particle entanglement is due to a high symmetry of the generated state. Entanglement manifests itself only in the collective properties of the two ensembles. Therefore a loss of coherence for a single atom makes a negligible effect on the entanglement, unlike in a maximally entangled multi-particle state this is one of the main advantages of using ensembels.

Now people believe that improving of trapping systems will allow to get better parameters than are now. But actually in this paper we are interesting in "real" solid devices so let's consider a few most promising systems for nonlocal entanglement.

2.5. GaAs quantum wells as a new medium for entanglement

In this section we are going to talk about new medium for entanglement. This medium is GaAs. In work [20] the was used DLSZ scheme[5] for preparing nonlocal entanglement but with on one difference it was proposed realization with an doped GaAs quantum well system. First of all we should say a few words about Imamoglu work [20]. He used that fact that the electronic spin degrees of freedom in semiconductors have coherence times that are much longer than other relevant timescales. Also he took into account that quantum dots QD behaves like an artificial atom only for a certain range of the applied gate voltage and the magnetic field. It was shown that it is possible to realize a quantum dot system with 2 or more low energy states with a long coherence time(more than 10 ns).So if we take into account that in GaAs we are able to use quantum Hall states which give selection rules for optical transitions across the gap. At the Fig.10 was shown schematic drawing of this system. In Fig. 10a the bulk GaAs electron levels are presented. In Fig. 11b you can see 2D electron system. By applying a strong magnetic field we are able obtain quantum Hall regime. It was considered quantum Hall state at filling factor $\upsilon = 1$ where is conduction-band Landau level is fully occupied (denoted as $|\downarrow\rangle$) and higher level is fully unoccupied. Fig. 10c allows for implementing a three-level system with the lowest spin-up and spin-down Landau levels. Fig .10 d depicts the optical transitions that can be used when the highest hole level is used for operating a three-level system.

Fig.11 present a device structure that was propused by athors [6]. The GaAs quantum well is embedded in an $Al_xGa_{1-x}As$ single-mode optical wavequide. Narrow electrical contacts on the side of this wavequide are used for in-situ monitoring of quantum Hall state of the electron ansemble.

The quantum well inside of wavequide contains a single electron ensemble. $Al_{03}Ga_{07}As$ is a core of waveguide(transparent for the optical field). The optimal choice of GaAs quantum well system width was chosen equal 20 nm. (consider best Zeeman splitting in this case)

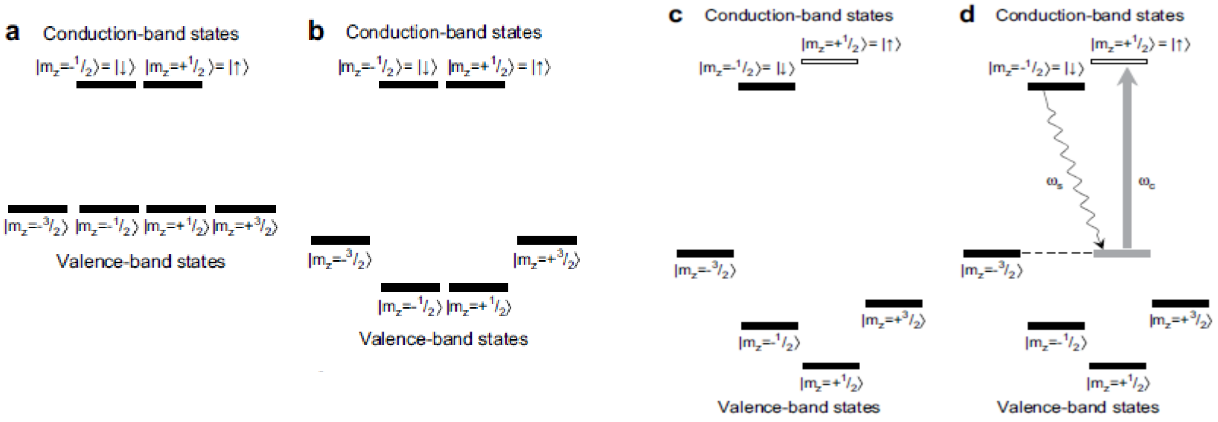

Fig. 11 a)Bulk n-GaAs; b)n-doped GaAs quantum well system with quantum confinement;

c)System in a magnetic field, bringing system in $\upsilon = 1$ quantum Hall state; d)effect of hole mixing are depicted, due to this effect the transitions labeled with ω_c and ω_s

Picture from [6].

Should note that unfortuanetly this proposal has a huge disadvantege that the quantum Hall effect wich was used, demands a very low temperature notably He temperatures, it makes this experiments very demanding and it is difficult to use it in real life.Finaly in this proposal for cration three level systems was used high-purity n-type GaAs under a strong magnetic field.We was able to isolated a lambda system composed of two Zeeman states of neutral-donor electrons. In this way decoherence time was obtained near 10 ns[39].

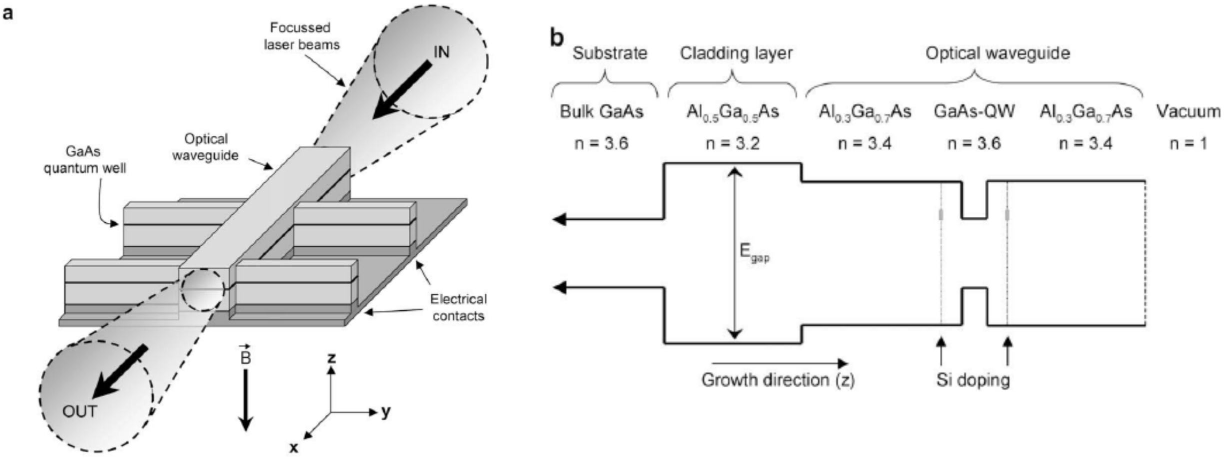

Fig. 11 a) Optical wavequide with an electron – spin ensemble in GaAs quantum – well, etched out of a GaAs/ with quantum confinement;c)System in a magnetic field, bringing system in $\upsilon = 1$ quantum Hall state; d)effect of hole mixing are depicted, due to this effect the transitions labeled with ω_c and ω_s . Picture from [6].

It is very important that the in these ensembles observed long spin coherence times for electron spin ensembles imply that the Zeeman splittings are very homogeneous. Due to this fact it is possible to generate Raman scattered fields from two different ensembles that are centered at identical optical frequencies and we tune it by using EIT bandwith. Also, two signal pulses have good spectral overlap this allows to generate Raman scattered fields from two different ensembles which centered at identical optical frequencies. So, due to these facts this proposal is promising for entanglement generation.

2.6. Donor-bound electrons in GaAs

Since we are interesting to realize nonlocal quantum entanglement between solid state devices and in previous paragraph we talked about semiconductor spin-based realization of this issue, for sure for us is very interesting to combine the optical accessibility and the possibilities of integrated device fabrication in III-V semiconductors. As we talked previously to make electron spins in GaAs medium, particularly, is very promising choice for realization of EIT and nonlocal quantum entanglement. . Theoretical research predicted long spin-flip lifetime (> ms) and long decoherence times (μs - ms) for electrons in GaAs quantum dots. In work [42], millisecond spin-flip lifetimes of donor electrons in high-purity GaAs were measured. In GaAS doped with silicon, Si dopants play usually the role of donor. At low temperatures(liquid helium temperatures) and at low doping concentrations $n \leq 10^{15}$ cm^{-3} the electron remains bound to the donor impurities.

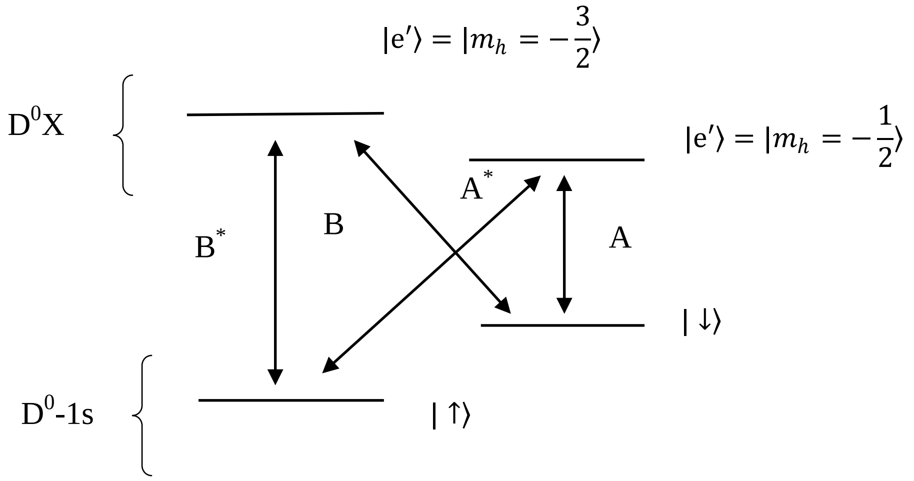

Fig. 12 Schematic picture of realization of Λ -system . Zeeman split are labeled as $|\downarrow\rangle$ and $|\uparrow\rangle$. The excited states are donor-bound exciton states (D^0X),with two electrons in a singlet state and a hole.Such pairs of transitions can be used for implementing in DLCZ scheme of realization nonlocal quantum entanglement

It is very important, this single electron is always present in contrast to the quantum dot case where the number of electron spins can be difficult to control. Like as with quantum dots, it is possible to excite a bound exciton (electron-hole pair). The total bound exciton (D0-X) complex is composed of two electrons in a spin-singlet state, one hole, and the donor impurity. Since each donor electron is in the same environment and has the same wavefunction , these system has little inhomgeneity and bulk optical transition line widths are several GHz. This parameter is more than three orders of magnitude narrower than quantum dots. The homogeneity in D0-X systems makes them atractive candidates for our applications because for successful realization of nonlocal quantum entanglement it is very necessary to have identical or nearly identical emitters.

Section 3

Summary and Outlook

In summary we have compare all possible techniques that allows us to realize nonlocal quantum entanglement between solid state devices. Before concluding we should note that remote entanglement of atomic qubits has been previously demonstrated using cold atomic clouds of ^{85}Rb or single trapped ^{171}Yb^{+} ions, as was mentioned at this paper above, but these experiments are only interesting for us because they shows clearly basic principles of realization of non-local quantum entanglement. Firstly we should realize entanglement of photonic and atomic qubits, and after that we should efficiently transfer quantum state from an atomic to a photonic qubit and also it is very crucial additional point is the reverse operation, in other words, a the conversion of a photonic qubit into an atomic qubit. These important steps enables the transfer of atom-photon entanglement into remote atomic qubit entanglement. In these paper we proposed to make experimental set-up for realization of nonlocal quantum entanglement between solid state devices with quantum optical control schemes which could based on there-level quantum systems which is the most suitable for such purpose. The difference only that we could realize three-level system using different materials and approaches so below we will try to answer which approach and materials are most promising for such purpose. In a present paper the most interest solutions of this issue was described, they include: quantum dots, semiconductor optical microcavities, impurities in semiconductors, nitrogen vacancy(NV) centers in diamond, electron ensembles in GaAs/AlxGa1-xAs structures. As we told previously firstly we have to realize entanglement of photonic and atomic qubits, for this we should have in our system long coherence time of electrons spins which influence on probability of get entanglement. If compare between all materials that was mentioned above, NV centers in diamond has the highest spin coherence time around 2 ms comparing for instance with GaAs/AlxGa1-xAs structures which has this parameter around 10 ns. But according theoretical predictions and measurements of properties of the donor-bound electrons in GaAs quantum wells and quantum dots structures was shown that
it is possible to have long spin-flip lifetime (> ms) and long decoherence times (μs - ms) for electrons in such structures. The second vary important issue is selective control for each transition on three-level system, as was shown in previous paragraph in all systems that was mentioned above is possible to realize it, but it is neccary to say , until recently was unknown about possibility to realize this technique in NV centers but was shown that it is also possible [36]. Third step that our system should provide a strong coupling to emitting node and with this task electron ensembles and microcavities manage better that nitrogen vacancy, but despite that fact that it is possible to use NV centers in cavity this issue needs furthe study. Next requirement is very close to the previous one, our system also should provide highly directional of emmiting signal, which also was shown could be easily realized in ensembles and cavity systems comparing for instance with NV centers. The fifth requirement is one

of the important one, because all transitions in two remote three-level systems should be identical because our optical set-up requires that spectrum of two optical pulses should be identical. As was shown Zeeman splittings for tree-level system that realized in electron ensembles in GaAs/AlxGa1-xAs structures and also for donor-bound electrons in GaAs(D0-X systems) are the same for each three-level system and near 0.25 meV in field of 10 T, so it gives our opportunity to apply DLCZ system which enables to increase probability of successful entanglement detection dramatically. But on of the huge barrier still exist is that the realization of entanglement in GaAs/AlxGa1-xAs is very demanding and difficult because we should use helium temeperature around 4 K and use extremely large magnitudes of magnetic filed around 10 T, and that's why still nonlocal entanglement has not been realized yet in such system because at this conditions noise is very huge and technically is very difficult to get valiable signal. Speaking about NV centers, this approach has a lot advantages, the most important one that we are able to work in room temperature and without magnetic field, but as we mentioned previously, in such system is extremely difficult to tealize to identical remote three-level systems even more to realize ensemble of three-level systems and that's why the probability of obtaining successful entanglement event is too very low. Finally it should be emphasized that NV centers and electron ensembles in GaAs/AlxGa1-xAs are very prommisimg approaches to non-local quantum entanglement realization they both have a lot advanteges and at most parameters could be compared with cold atomic clouds, vapors and identical trapped ions where this realization was successful shown but both this approaches have a lot disadvantages which still prevent to realize non-local entanglement in solid states.Experiments in the last years showed that only technical realization prevent to get successful result, so it is not doubt that in the near future all technical problems concerning realization of non-local quantum entanglement in such system will be solved. Also it is very exsisting area of physics and it seems reasonable to suggest that some techniques that was described here will find some future applications in science and technology.

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