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# CNOT on polarization states of coherent light

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We propose a CNOT gate for quantum computation. The CNOT operation is based on the existence of triactive molecules which in one direction have electric dipole moment and cause rotation of the polarization of linearly polarized light, and in a perpendicular direction have a magnetic dipole moment. The incoming linearly polarized laser beam is divided into two beams by a beam splitter. In one beam a control state is prepared and the other beam is a target. Arguments are given to show that the interaction of polarized states of both beams in a solution containing the triactive molecules can be described as the interaction of two qubits in CNOT.

**Keywords:** CNOT gate; magnetooptical effects.

Proponemos una compuerta CNOT para cómputo cuántico. La operación CNOT se basa en la existencia de moléculas triactivas las cuales en una dirección tienen un momento dipolar eléctrico y causan la rotación de la polarización de luz linealmente polarizada, y en una dirección perpendicular tienen un momento dipolar magnético. Mediante un divisor de haz, el haz polarizado incidente se divide en dos haces. En uno de ellos se prepara el estado de control y el otro se considera haz blanco. Se dan argumentos para mostrar que la interacción de los estados de polarización de ambos haces en una solución que contenga a las moléculas triactivas puede ser descrita como la interacción de dos qubits en una compuerta CNOT.

**Descriptores:** Compuerta CNOT; efectos magnetópticos.

PACS: 0.3; 67.Ac; 03.67.Lx; 78.20.Ls

## 1. Introduction

Numerous investigations have proposed various physical ways to implement an operating CNOT gate which is one of the basic elements for quantum computing [1, 2]. Our proposal is based on the manipulation of polarization states of a laser beam which has many advantages in technological aspects that are not necessary to describe. The polarization state of completely polarized light can be described by the same mathematics as a qubit. A geometric representation of both quantities is provided by the Poincaré (or the Bloch) sphere.

In order to be able to construct the proposed CNOT gate, triactive molecules are needed as a basic ingredient. When polarized light passes through a solution of an optically active compound – chiral or optical isomers or optical polymers – the direction of polarization is rotated to the right or to the left. Recent development in the chemistry of such dipole molecules with controlled optical properties opens the opportunity to ask chemists to prepare such an isomer or polymer molecule with one more property - with magnetic dipole moment oriented perpendicularly to the electric dipole moment as shown in Fig. 1. In instance, we need to implement a magnetic dipole moment to some chiral isomer or polymer, with high anisotropic polarizabilities as described in Ref. 4. Thus we need a molecule with the following properties:

- It has an electric dipole moment  $\vec{p}$ .
- It has a property of optical activity in one direction  $\vec{a}$ , *i.e.*, the direction of polarization of passing linearly polarized light rotates due to interaction with the molecules whose  $\vec{a}$  is oriented parallel with the ray

( $\vec{a}$  and  $\vec{p}$  are often parallel (let us suppose it in the following)).

- It has a magnetic dipole moment  $\vec{m}$  perpendicular to directions  $\vec{a}$  and  $\vec{p}$ .

It can be expected that modern chemistry can produce such molecules, since molecules with the first two properties, *i.e.* without magnetic moment, have already been produced. For molecules with electric moment see [4]. Moreover, the engineering of core-shell nanoparticles can be used to produce triactive molecules [5].

## 2. Operation

For the sake of describing the principle of operation we will consider completely linearly polarized light.

Let us have a concentration  $n$  of such triactive molecules in a homogeneous solution, under thermal motion they rotate in all directions; the distribution of dipole moments of molecules is the same in all directions and the polarization density is  $\vec{P} = 0$ . The angle of rotation of polarization of passing light will depend only on the length of path of light in the solution.

Putting the solution in a strong homogeneous magnetic field in an ideal case guarantees that the thermal rotation of the molecules will be restricted to the precession of the magnetic moments around the direction of the magnetic field. The magnetic field thus breaks the isotropy of optical activity of solution. After switching the magnetic field, the angles of rotation of polarization of light in the directions parallel and perpendicular to the magnetic field at the same distance are

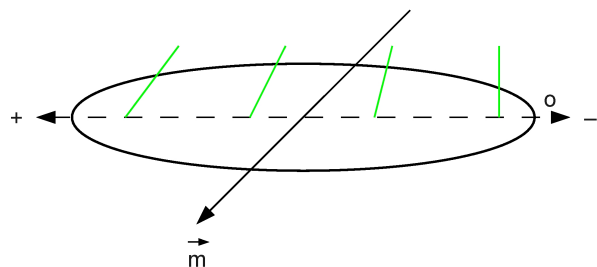


FIGURE 1. Scheme of a triactive molecule. Molecule has magnetic moment  $\vec{m}$  in the direction perpendicular to the electric dipole moment, and the direction of the electric dipole moment (dashed line) is the axis of rotation of the direction of polarization - green lines.

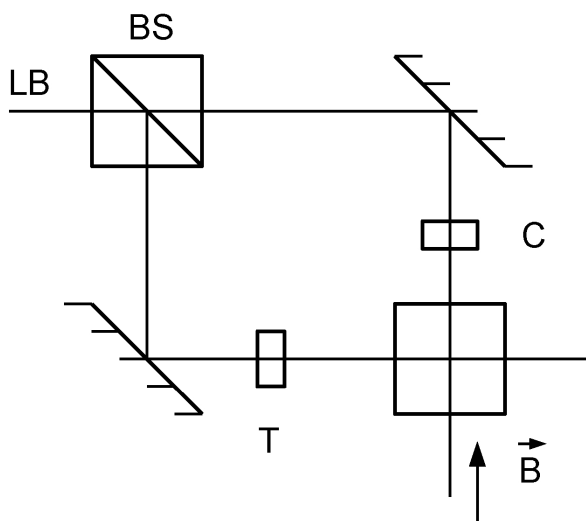


FIGURE 2. Scheme of CNOT in operation. The laser beam (LB) is divided by the beam splitter (BS) into control and target parts. Control and target states are prepared using C and T which manipulate the polarization in each state. The control and target beams then enter the CNOT cell. Control part passes through the cell in the direction of external magnetic field  $\vec{B}$  and target part in perpendicular direction.

no more equal. The resulting angle of rotation of polarization plane of passing light depends on the length of path of the light in the solution and on the angle between the incident ray and the magnetic field.

Next switching an electric field in a direction perpendicular to the magnetic field, the rotational symmetry in the plane perpendicular to the magnetic field is broken. The polarization density will essentially have the direction of electric field. The angle of rotation of polarization (passing the same distance in solution) will be minimal in the direction of magnetic field and maximal in the direction of electric field.

Let us send two light beams through the solution in two perpendicular directions, the first of them being parallel with the magnetic field and the second perpendicular.

The oscillating electric field of the light beam parallel with the magnetic field controls the absolute value of polar-

TABLE: CNOT operations on polarization states of beams

Input control	Input target	Output control	Output target
$\rightarrow$	$\rightarrow$	$\rightarrow$	$\rightarrow$
$\rightarrow$	$\uparrow$	$\rightarrow$	$\uparrow$
$\uparrow$	$\rightarrow$	$\uparrow$	$\uparrow$
$\uparrow$	$\uparrow$	$\uparrow$	$\rightarrow$

ization density of the illuminated solution, and the polarization state of this beam does not change (in an ideal case of low temperature). The polarization of the light beam perpendicular to the magnetic field will rotate around with respect to the direction and an intensity of the first beam. Moreover, it can also influence the mean absolute value of polarization density of solution when the polarization of the second beam is not parallel with the magnetic field.

The angle of rotation of the polarization of the beam perpendicular to the magnetic field will depend on the direction of the polarization density of the solution, which will lie in the plane perpendicular to the magnetic field. Of course, the dependence of the angle of rotation of the polarization on the temperature as well as the length of the path of the beam in the solution have to be taken into consideration to guarantee the correct function of the proposed CNOT gate.

### 3. How does it work?

The operation of the CNOT gate can be described as follows:

1. The linearly polarized laser beam (LB) is divided into two parts by the beam splitter (BS), see Fig. 2.
2. The optical devices C and T in the two branches prepare the polarization states according to the requirement for the input states in CNOT cell.
3. One of the divided beams which passes the CNOT cell with the solution of triactive molecules parallel with the external magnetic field plays the role of the control qubit and the other is the target qubit. Both beams pass the CNOT cell simultaneously.

The control beam determines the magnitude of the absolute value of the polarization density in cube and the direction of the polarization of passing light. According to the Langevin-Debye theory the mean value of the polarization density is

$$\langle |P| \rangle = \frac{np^2\pi}{\sqrt{2}kT} E_C,$$

where  $\vec{E}_C$  is an amplitude of the vector of the intensity of electric field of control beam, and the direction of the polarization density is given by the direction of linearly polarized light in the control channel. The influence the vector of the target electric field is negligible because it rotates several times when passing the CNOT cube.

The nonzero mean value of the magnitude of the vector of polarization density in the described direction is the crucial point for the operation of the CNOT. If the direction of polarization of the control beam will be parallel with the direction of target beam, the polarization of target beam will rotate more than in the case where the direction of polarization of the control beam will be perpendicular to the direction of target beam. The direction of polarization of control beam is not changed because the magnetic field does not allow significant changes of the polarization density of solution in direction of control beam. So one can control the geometry of the cube, concentration of triactive molecules in the solution and temperature to fit the difference between the polarization planes of the target beam of two previous cases after passing the cube.

The operation is shown in Fig. 2. Let  $|0\rangle$  be polarization state of linearly polarized light perpendicular to the plane of figure – vertical polarization, and  $|1\rangle$  in the plane – horizontal polarization. Having the input state  $|1\rangle$ , after splitting the

state is  $|1\rangle \otimes |1\rangle$ . The device C change the state  $|1\rangle$  into  $|\gamma\rangle$  and T change the state  $|1\rangle$  into  $|\tau\rangle$ . The state on inputs in cube is  $|\gamma\rangle \otimes |\tau\rangle$ . On the output of cube the state is  $|\gamma\rangle \otimes |\tau - \gamma\rangle$ .

## 4. Conclusion

The magnetic dipole moment is in principle necessary in order to fix an axis of rotation of molecules. The same effect can be achieved also by other means, e.g. ordering of optically active dipole molecules in material with a preferred plane of change in polarizability.

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