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NUCLEAR TELEPORTATION (PROPOSAL FOR AN EXPERIMENT)

B. F. Kostenko [a1], *V. D. Kuznetsov* [a], *M. B. Miller* [b], *A. V. Sermyagin* [b], *D. V. Kamanin* [a]

[a] Joint Institute for Nuclear Research, Dubna

[b] Institute of Physical and Technology Problems, Dubna

Since its discovery in 1993, quantum teleportation (QT) is a subject for intense theoretical and experimental efforts. Experimental realizations of QT have so far been limited to teleportation of light. The present letter gives a new experimental scheme for QT of heavy matter. We show that the standard experimental technique used in nuclear physics may be successfully applied to teleportation of spin states of atomic nuclei. It was shown that there are no theoretical prohibitions upon a possibility of a complete Bell measurement, so that implementation of all four quantum communication channels is at least theoretically available. A general expression for scattering amplitude of two $\frac{1}{2}$-spin particles was given on the Bell operator basis, and peculiarities of the Bell states registration are briefly discussed.

С момента открытия в 1993 г. квантовая телепортация (КТ) является предметом интенсивных теоретических и экспериментальных исследований. Экспериментальная реализация КТ до настоящего времени осуществлена лишь для квантов света. В настоящей работе приводится новая экспериментальная схема для телепортации тяжелой материи. Показывается, что стандартная экспериментальная техника, используемая в ядерной физике, с успехом применяется для телепортации спиновых состояний атомных ядер. Установлено, что нет никаких теоретических запретов на осуществление полного белловского измерения. Это означает, что реализация всех четырех возможных квантовых каналов передачи информации, по крайней мере теоретически, возможна. Дано общее выражение для амплитуды рассеяния двух частиц со спином $\frac{1}{2}$ в операторном базисе Белла, а также кратко описаны особенности регистрации белловских состояний.

INTRODUCTION

Not long ago only science fiction authors ventured to use a term «teleportation». However in the last few years the situation drastically changed. In a landmark work [1] a procedure for teleporting an unknown quantum state from one location to another was described. Recent experiments have proved that this process can actually happen [2, 3]. Now invention of QT is expected to have a great influence on the future computation and communication hardware comparable with the impact of radio network on modern technique. It may have important applications in superfast quantum computers (theoretical at present) [4–7] as well as in utilizing quantum phenomena to ensure a secure data transmission (by means of the so-called quantum cryptography) [8–10]. Practical realization of quantum information processing

[1] e-mail: kostenko@cv.jinr.ru

requires special quantum gates which cannot be performed through unitary operations, but may be constructed with the use of quantum teleportation for a basis element [11]. Recently a one-to-one correspondence between quantum teleportation and dense coding schemes was established as well [12].

Besides a relevancy to such applications as quantum computing, QT is also a new fundamental concept in quantum physics. Experimental demonstrations show that QT is an experimentally achievable technique to study the phenomenon of quantum entanglement. Indeed, the very phenomenon of QT appeared to be possible only due to the Einstein–Podolsky–Rosen correlations (see below), which till now are confirmed exactly only for photons. The same is true for QT, because only entangled optical beams have been so far used to teleport quantum states of massless matter.

Since quantum information processing involves material particles such as atoms and ions, teleportation of heavy matter is considered now as the next necessary step for obtaining a complete set of quantum processing tools [13–16].

We propose here a new experimental scheme for QT of heavy matter based on a standard experimental nuclear physics technique and expected to be fulfilled in the nearest one or two years. To the best of our knowledge other methods require at least ten years to be successful.

ACTION-AT-A-DISTANCE (TELEPORTING INFORMATION)

In 1935, Albert Einstein and his colleagues Boris Podolsky and Nathan Rosen (EPR) developed a gedanken experiment to show as they believed a defect in quantum mechanics (QM) [17, 18]. This experiment has got the name of EPR-paradox. An essence of EPR-paradox is as follows. There are two particles that have interacted with each other for some time and have constituted a single system. In the QM that system is described by a certain wave function. When the interaction is terminated and the particles flew far away from each other they are as yet described by the same wave function. However individual states of each separated particle are completely unknown. Moreover, definite individual properties do not exist in principle as the QM postulates prescribe. It is only after **one** of the particles is registered by a detection instrument that the states arise to existence for **both** of them. Furthermore, these states are generated simultaneously regardless of the distance between the particles at the moment. It looks like one particle informs instantly the other of its state.

The real (not just «gedanken») experiments on teleportation of information of this type, or «a spooky-action-at-a-distance», as A. Einstein called it, were carried out only 30–35 years later, in the seventies-eighties [19,20]. Experimenters, however, managed to achieve full and definite success only for photons, though attempts to perform experiments with atoms [21] and protons were also undertaken [22]. For the case of two photons the experiments were carried out for various distances between them at the moment of registration, and the EPR-correlations were shown to survive up to as large distances as more than ten kilometers [23]. In the case of protons, an experiment was carried out only for much less distances of about a few centimeters and the condition of causal separation, $\Delta x > c\Delta t$, was not met. Thus it was not fully persuasive, as have been recognized by the authors of the work [22] themselves.

TELEPORTING PHOTON-QUANTUM STATE (OR THE LIGHT QUANTUM ITSELF?)

The next step in this direction that suggested itself was not merely the «action-at-a-distance», but transmission of a quantum state from one quantum object to another. Namely, this process was called QT. In spite of the successful EPR-effect experiments, until recently even this kind of teleportation was believed to be impossible at all. At first sight it seems as Heisenberg uncertainty principle would forbid the very first step of the teleportation which was meant as an extraction of complete information about the inner properties of a quantum object to be teleported. But it cannot be done because of the impossibility of measuring simultaneously exact values for the so-called complementary variables of a quantum microscopic object (e. g., spatial coordinates and momenta). Nevertheless, in 1993, a group of physicists (C. Bennet and his colleagues) managed to get round this difficulty [1]. They showed that measurement of full quantum information is not necessary for quantum states transferring from one object to another. Instead, it was proposed to create the so-called EPR-channel of communication on the basis of EPR-pair of two quantum particles. Let it be photons B and C, shown in Fig. 1. After they have interacted in a way to form a single system, decaying afterward, the photon B is directed to the «point of departure», where it meets A within a registration system. The system is arranged in a mode (see below) to «catch» only those events which leave no choice to C but to take a state that A had initially (before its interaction with B in the detector at the «point of departure»). This experimental technique is very fine but well known to those skilled in the EPR-art.

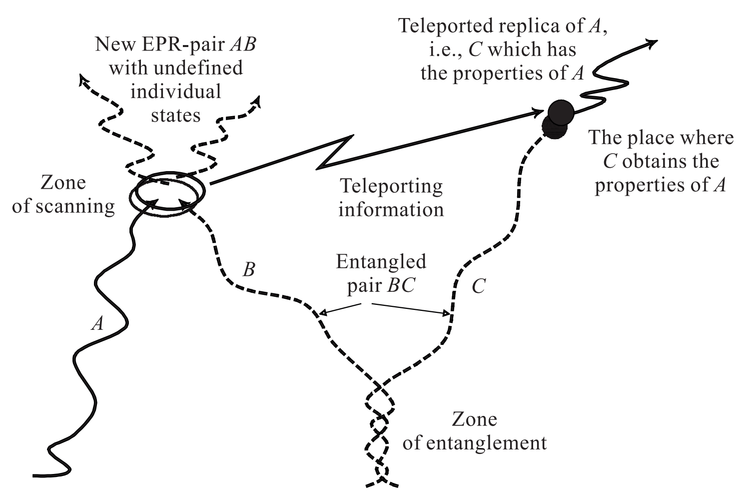

Fig. 1. Illustration of a general idea how the teleportation can be realized. Here A is a photon we want to pass to a destination place; B and C, representing an EPR-pair of photons, constitute the so-called quantum transmission channel. As a result, definite properties of A are destroyed completely at the zone of scanning, and at another place we have the photon C with the properties A had just before it met intermediary object B («vehicle»). Note that the vehicle first contacts the C photon to which the «cargo» has to be transported, and only later it calls A to take the cargo from it

What is important from the principal point of view, it is «disappearing» of A in the place, notified in Fig. 1 as «zone of scanning» (ZS). Indeed, interaction of B and A destroys the A photon, in a sense that none of the two photons outgoing from ZS has definite properties of A. They constitute a new pair of photons, which only as a whole has some quantum state, and the individual components of the pair are deprived of this property. Therefore, in some sense the photon A really disappears at ZS. Exactly at the same moment the photon C obtains the properties A had in the beginning. Once it happened, in view of the principle of identity of elementary particles, we can say that A, disappearing at ZS, reappears at another location. Thus, the quantum teleportation is accomplished.

This process has several paradoxical features. In spite of the absence of contacts between objects (particles, photons) A and C, A manages to pass its properties to C. It may be arranged in such a way that the distance from A to C is large enough to prevent any causal signals between them! Furthermore, in contrast to the transportation of ordinary material cargo, when a delivery vehicle first visits the sender to collect a cargo from it, quantum properties are delivered in a backward fashion. Here the photon B plays a role of the delivery vehicle, and one can see that B first interacts with the recipient (C photon) and only after that it travels to the sender (A) for the «cargo».

Finally, to reconstruct initial object completely it is necessary to inform a receiver at the destination about a result of the measurement in ZS. This allows him to accomplish processing of quantum signal (incoming with the particle C) in a due manner. Therefore, one more channel of communication is needed for an ordinary or classical information transmission. Only receiving a message (using the classical communication line) that A and B form a **new EPR-pair with zero total spin**, an observer at destination may be sure that the properties of C are identical to those of A before teleportation. In the case when $A + B$ system has nonzero total spin, some additional transformation of quantum signal is needed (see below).

The new idea was immediately recognized as an important one and several groups of experimenters set to implement it concurrently. Nevertheless, it took more than four years to overcome all technological obstacles on the way [2, 3]. That was because such experiments, being the records, are always a step beyond the limits of experimental state of the art achieved before.

START WITH PROTONS

The purpose of this paper is to show that experimental set-ups and instruments developed for conventional nuclear-physics studies allow one to design a new way of performing nonzero mass matter teleportation, with a prospect to implement the project in a rather short time. For example, in accordance with our estimates, teleportation of protons could be achieved in one or two years.

In Fig. 2, the layout of an experiment on teleportation of spin states of protons from a polarized PH_2 target into the point of destination (target C) is shown. A proton beam p_0 of a suitable energy within the range of 20–50 MeV bombards the LH_2 hydrogen target [24]. According to the known experimental data, the scattering in the LH_2 target onto the direction of the second target (corresponding the angle $\theta \simeq 90°$ at the c. m.) occurs within an acceptable accuracy through the singlet intermediary state [22]. Thus, the outgoing protons p_2 and p_3 form the two-proton entangled system fully analogous to the EPR-correlated photons used in

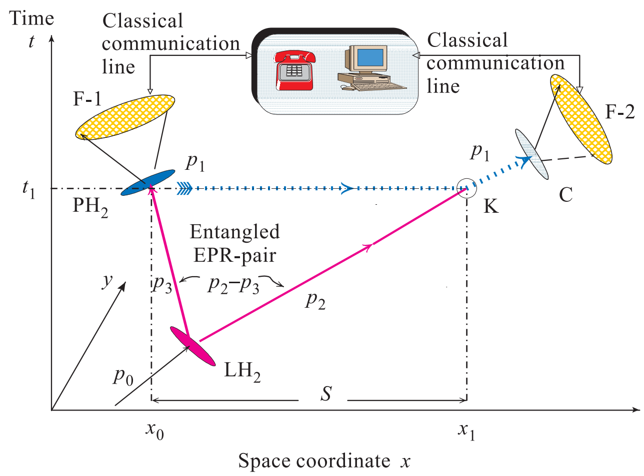

Fig. 2. Layout of experiments on proton teleportation. Here p_0 is initial proton from the accelerator, LH$_2$ is a liquid hydrogen target, which may be also replaced by ordinary polyethylene (CH$_2$) foils, protons p_2 and p_3 constitute an entangled EPR-pair, PH$_2$ denotes polarized hydrogen target, C is a carbon target which operates as an analyzer of the proton polarization using the left-right asymmetry of scattering, F-1 and F-2 are large-aperture position-sensitive particle detectors (the so-called Fobos-facilities). Proton spin-state is being teleported from the PH$_2$ target placed at x_0 to the point x_1. K is a point where the spin of p_2 gets a definite orientation (which is just the same that one of the protons p_1 in the PH$_2$ target had before the scattering of p_3 from it). The proton p_1 losses its definite quantum state, as it forms a new EPR-pair together with the scattered proton P_3. The role of classical communication channel including a data-processing centre is explained in the text

the experiments on the teleportation of massless matter, as it was discussed in the preceding section. At this moment the system is in a state

$$|\Psi_{23}\rangle = \frac{1}{\sqrt{2}} \left(|\uparrow_2\rangle |\downarrow_3\rangle - |\downarrow_2\rangle |\uparrow_3\rangle \right).$$

One of the scattered protons, p_2, then travels to the point of destination (the target-analyzer C), while the other, p_3, arrives to a point where teleportation is started, i. e., to PH$_2$ target. The last one is used as a source of particles to be teleported. Therefore, protons within this target play the same role as the photons A in the above section. But there are two features differentiating the case of protons from the photon one. First, the protons p_1 are within the motionless target (and thus they are motionless themselves) with a much more proton density; besides, the protons within the PH$_2$ target have quite definite quantum state, determined by a direction of polarization,

$$|\phi_1\rangle = a|\uparrow_1\rangle + b|\downarrow_1\rangle$$

which could be oriented accidentally and, thus, unknown to the experimenters.

In the case, when the scattering in the polarized PH$_2$ target occurs in the same kinematics conditions as in the LH$_2$ target (i. e., at the c. m. angle $\theta \simeq 90°$), the total spin of the particles

p_1 and p_3 also must be equal to zero after collision. To detect the events, a removable circular module F-1 of the facility «Fobos» is supposed to be used [25]. Due to this fact, the detection efficiency is hoped to be much enhanced. If all the above conditions are provided, the protons reaching a point K will suddenly receive the same spin projections as the protons in the polarized [26] PH_2 target. Indeed, using the so-called Bell's basis,

$$|\Psi_{13}^{(\pm)}\rangle = \frac{1}{\sqrt{2}}\,(|\uparrow_1\rangle|\downarrow_3\rangle \pm |\downarrow_1\rangle|\uparrow_3\rangle)\,,$$

$$|\Phi_{13}^{(\pm)}\rangle = \frac{1}{\sqrt{2}}\,(|\uparrow_1\rangle|\uparrow_3\rangle \pm |\downarrow_1\rangle|\downarrow_3\rangle)\,,$$

the state of three-particle system before the last scattering may be written in the form

$$|\Psi_{123}\rangle = |\phi_1\rangle|\psi_{23}\rangle = \frac{1}{2}[\,|\Psi_{13}^{(-)}\rangle(a|\uparrow_2\rangle + b|\downarrow_2\rangle) + |\Psi_{13}^{(+)}\rangle(a|\uparrow_2\rangle - b|\downarrow_2\rangle) + \\ + |\Phi_{13}^{(-)}\rangle(-a|\downarrow_2\rangle - b|\uparrow_2\rangle) + |\Phi_{13}^{(+)}\rangle(-a|\downarrow_2\rangle + b|\uparrow_2\rangle)\,].$$

The last scattering and measurement with F-1 select from this state the term containing $|\Psi_{13}^{(-)}\rangle$, and therefore the state of the particle 2 will be $a|\uparrow_2\rangle + b|\downarrow_2\rangle$. Thus, if the coincidence mode of the detection is provided via any classical channel, then a strong correlation has to take place between polarization direction in the PH_2 target and the direction of the deflection of p_2 protons scattered in the carbon target C. Here the carbon foil C plays a role of the polarization analyzer, i. e., one measures the asymmetry of the left-right counting rates to determine a spin state orientation of p_2 before the scattering [27].

In particular, if one succeeds to make a distance between the detectors F-1 and F-2 to be sufficiently large and the difference between the moments of registration in F-1 and F-2 to be short enough, then it will be possible to meet the important criteria of the causal independence between the events of the «departure» of the quantum state from PH_2 target and «arrival» of this «cargo» to the recipient (proton p_2) at the point K. The measurements consist of recording signals entering two independent but strictly synchronized memory devices with the aim to select afterward those events alone that for sure appeared to be causal separated. Thus, experimental set-up shown in Fig. 2 also allows one, at least in principle, to fill the gap in verification of the EPR-effect for heavy matter.

GENERAL CONSIDERATION

In the experiments that were carried out until now it was managed to use only one quantum information transmission channel corresponding to registration of Bell's state $|\Psi_{13}^{(-)}\rangle$. Is it possible to involve other channels utilizing the states $|\Psi_{13}^{(+)}\rangle$, $|\Phi_{13}^{(-)}\rangle$, and $|\Phi_{13}^{(+)}\rangle$? To answer this question let us consider a general expression for scattering amplitude of two particles, not necessarily identical ones, with the spin value $\frac{1}{2}$ [28],

$$\hat{f} = A + B(\mathbf{S}_1\boldsymbol{\lambda})(\mathbf{S}_2\boldsymbol{\lambda}) + C(\mathbf{S}_1\boldsymbol{\mu})(\mathbf{S}_2\boldsymbol{\mu}) + D(\mathbf{S}_1\boldsymbol{\nu})(\mathbf{S}_2\boldsymbol{\nu}) + \\ + E((\mathbf{S}_1 + \mathbf{S}_2)\boldsymbol{\nu}) + F((\mathbf{S}_1 - \mathbf{S}_2)\boldsymbol{\nu}).$$

Using a relation

$$(\mathbf{S}_1\mathbf{n})(\mathbf{S}_2\mathbf{n}) = \frac{1}{2}\left[((\mathbf{S}_1+\mathbf{S}_2)\mathbf{n})^2 - \frac{1}{2}\right],$$

in the case of the coordinate system to be fixed for a definiteness in the following way

$$\boldsymbol{\lambda} \parallel \mathbf{x}, \quad \boldsymbol{\mu} \parallel \mathbf{y}, \quad \boldsymbol{\nu} \parallel \mathbf{z},$$

the expression for $\hat{f}$ can be represented in the form

$$\hat{f} = A + \frac{B}{2}\left[S_x^2 - \frac{1}{2}\right] + \frac{C}{2}\left[S_y^2 - \frac{1}{2}\right] + \frac{D}{2}\left[S_z^2 - \frac{1}{2}\right] + ES_z - Fs_z,$$

where

$$\mathbf{S} = \mathbf{S}_1 + \mathbf{S}_2\,, \qquad \mathbf{s} = \mathbf{S}_1 - \mathbf{S}_2.$$

The scattering operator $\hat{f}$ can be now expressed in terms of the Bell's state transition operators making use of the following formulas

$$\begin{aligned}
S_x &= |\Psi^{(+)}\rangle\langle\Phi^{(+)}| + |\Phi^{(+)}\rangle\langle\Psi^{(+)}|,\\
S_y &= i\left[|\Psi^{(+)}\rangle\langle\Phi^{(-)}| - |\Phi^{(-)}\rangle\langle\Psi^{(+)}|\right],\\
S_z &= |\Phi^{(-)}\rangle\langle\Phi^{(+)}| + |\Phi^{(+)}\rangle\langle\Phi^{(-)}|,\\
s_z &= |\Psi^{(+)}\rangle\langle\Psi^{(-)}| + |\Psi^{(-)}\rangle\langle\Psi^{(+)}|
\end{aligned}$$

and a decomposition of the unity $\hat{\mathbf{1}} = \hat{P}_{\Psi-} + \hat{P}_{\Psi+} + \hat{P}_{\Phi-} + \hat{P}_{\Phi+}$. As a result one obtains

$$\hat{f} = a\hat{P}_{\Psi-} + b\hat{P}_{\Psi+} + c\hat{P}_{\Phi-} + d\hat{P}_{\Phi+} + ES_z + Fs_z, \tag{1}$$

where

$$a = A - \frac{B+C+D}{4}, \qquad b = a + \frac{B+C}{2}, \qquad c = a + \frac{C+D}{2}, \qquad d = a + \frac{B+D}{2}.$$

In the case $E = F = 0$, expression (1) is a usual spectral decomposition for the operator $\hat{f}$, which can be interpreted then as a quantum observable corresponding to measurement of one of the Bell's state. Therefore, to register a definite Bell's state one has to find such experimental conditions at which all coefficients but one of a, b, c, or d in the expression (1) turn into zero. For these purposes, the type and energy of colliding particles, as well as the angle which scattered particles are recorded at, could be altered. Since the number of necessary conditions formulated above is less than the number of free coefficients in (1), it is clear that registration of each Bell's state is possible at least theoretically.

Directions which spin projections of the scattered particles should be measured along for detecting the states $|\Psi^{(+)}\rangle$, $|\Phi^{(-)}\rangle$, and $|\Phi^{(+)}\rangle$ form three orthogonal spatial vectors. It follows from the relations

$$|\Psi^{(+)}\rangle = \mathbf{e}_1\,, \quad |\Phi^{(\pm)}\rangle = \frac{1}{\sqrt{2}}(\mathbf{e}_2 \pm \mathbf{e}_3),$$

where $\mathbf{e}_i$ are orthonormalized states with the definite values of the spin and its projections,

$$\mathbf{e}_1 = |1,0\rangle\,, \quad \mathbf{e}_2 = |1,1\rangle\,, \quad \mathbf{e}_3 = |1,-1\rangle\,,$$

which transform in accordance with 3-vector representation of the rotational group. It is clear that spatial rotations at the angle $\frac{\pi}{2}$, corresponding to $\mathbf{e}_i \to \pm\mathbf{e}_j$, represent the group of permutation for the Bell's states considered (putting aside an unimportant phase factor -1). Thus the possibility of registration of $|\Psi^{(+)}\rangle$ state also opens the way to register two other states $|\Phi^{(+)}\rangle$, $|\Phi^{(-)}\rangle$ by means of change on $\frac{\pi}{2}$ of the direction along which the spin projection is measured.

For identical $\frac{1}{2}$-spin particles the scattering operator (1) has some additional symmetries, so that in c. m. s. one has

$$\begin{aligned}
a(\theta) &= \ a(\pi-\theta), \qquad & b(\theta) &= -b(\pi-\theta),\\
c(\theta) &= -c(\pi-\theta), \qquad & d(\theta) &= -d(\pi-\theta),\\
E(\theta) &= \ E(\pi-\theta), \qquad & F(\theta) &= F(\pi-\theta).
\end{aligned}$$

For nucleon–nucleon scattering we have $F \equiv 0$ as total spin squared of such a system is conserved and the last two terms in (1) describe transitions between Bell's state with different $\mathbf{S}^2$. Thus, e. g., for two identical nucleons at $\theta = \frac{\pi}{2}$ one obtains

$$\hat{f} = a\hat{P}_{\Psi^-} + E\left[|\Phi^{(-)}\rangle\langle\Phi^{(+)}| + |\Phi^{(+)}\rangle\langle\Phi^{(-)}|\right].$$

Experimental identification of Bell's states $|\Psi^{(-)}\rangle$ and $|\Psi^{(+)}\rangle$ is rather simple due to the characterization of these states by the definite values of total spin and its projections ($|\mathbf{S}| = 0$, $S_z = 0$, and $|\mathbf{S}| = 1$, $S_z = 0$, respectively). The result of spin projection measurement for the particles 1 and 3 is

$$S_{z1} = \pm\,\frac{1}{2}\,, \quad S_{z3} = \mp\,\frac{1}{2}$$

for any choice of z axis direction, provided their initial state is $|\Psi^{(-)}\rangle$.

For particles in the $|\Psi^{(+)}\rangle$ state such correlations take place only if the spin projections are measured along a definite axis $\mathbf{n}$. If the axis of measuring is deflected at an angle θ from this direction, the probability to have $S_{z1} + S_{z3} = 0$ will decrease as $\cos^2\theta$. One may expect that at the energies considered, there is a scattering angle interval corresponding to $l = 1$ and, therefore, to the $|\Psi^{(+)}\rangle$ final state of two protons.

It seems more difficult to identify states $|\Phi^{(-)}\rangle$ and $|\Phi^{(+)}\rangle$. In this case, it is necessary first to find out a direction $\mathbf{n}'$ (which is perpendicular to $\mathbf{n}$) for which measurements of spin projections give either $S_{z1} = \frac{1}{2}$ and $S_{z3} = \frac{1}{2}$ or $S_{z1} = -\frac{1}{2}$ and $S_{z3} = -\frac{1}{2}$ with the same probability $p = 0.5$. Now measurement of the spin projection of the particle 2 allows one to determine what of two possible states, $|\Phi^{(-)}_{13}\rangle$ or $|\Phi^{(+)}_{13}\rangle$, the scattering has really occurred into.

CONCLUSION

Referring to the principle of identity of elementary particles of the same sort with the same quantum characteristics, i. e., the protons in our case, we can say that protons from a polarized target PH_2 are transmitted to the destination point C (through the point K). Thus, in the nearest future, teleportation of protons can come from the domain of dreams and fiction to the reality in the physicists' laboratories.

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