Nuclear Teleportation

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Until recently, only science-fiction authors ventured to use a term teleportation. However, in the last few years, on the eve of upcoming new millennium, the situation changed very much. The present report gives a synopsis of main concepts in this area. The readers will be able to make sure that paradoxical phenomena in the microcosm give a possibility to demonstrate the exchange of properties between microobjects, removed at a very large distance from each other, when no forces act between them. A new experimental scheme with hydrogen and helium nuclei is proposed. It is expected that the results of these experiments will be considered as teleportation of nuclear properties of atoms of the simplest chemical elements. A problem of teleportation of the more palpable cargo is left to the physics of the more distant future.

Introduction

It was in the middle of twenties that an analysis of transportation of soya beans on the Chinese Eastern Railway was carried out. It appeared that counter transportation constituted a greater share of the total cargo traffic. Then an original procedure of processing the cargoes was invented: in the number of cases it was possible to deliver bean lots to recipients from the nearest stations, where at that time there was a sufficient amount of beans of a corresponding category, intended, though, to be sent to some other and more remote points. Economy of a rolling stock and other advantages for the railway were obvious. The history fails to mention how this innovation ended. Probably the complicated events on the CER in the beginning of the thirties put an end to the promising experiment. Nevertheless, this was perhaps a first attempt to realize the supertransportation of dry substances, or particulate solids.

The process of teleportation (commonly accepted term for supertransportation) according to usual understanding is reduced to moving through space in such a way that the object to be transported disappears at one spot of space and reappears exactly at the same time in some other point. It is well understood that it is not necessary to move through the space the matter the object is composed of. It is enough to extract an exact information about inner properties of the object, then transmit this information to a predetermined place, and use it afterward to reconstruct the initial object from a stuff that comes to hand at the point

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of destination. Thus the teleportation results in disappearing of the object with its initial properties in the initial place and the identical object to reappear in another place. Without disappearing it would not be the teleportation, but merely a reproduction, i.e. a creation of a new identical specimen, or a copy of the object. Let us look how physicists cope with this problem.

**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 thought a defect in quantum mechanics (QM) \[1,2\]. This experiment has obtained the name of the EPR-paradox, and essence of the paradox is as follows. There are two particles that interacted with each other for some time and have constituted a single system. Within the framework of QM that system is described by a certain wave function. When the interaction of the particles is finished and they flew far away from each other, these two particles are still described by the same wave function as before. However, individual states of each separate particle are completely unknown, moreover, definite individual properties do not exist in principle as quantum mechanics postulates dictate. It is only after one of the particles is registered by a particle-detection system that the states arise to existence for both particles. Furthermore, these states are generated instantly and simultaneously regardless of the distance between the particles at the moment. This scheme is used to be considered sometimes as teleportation of information possible at a speed higher than that of light. The real (not only "gedanken") experiments on teleportation of information, in the sense of EPR-effect, or "a spooky-action-at-a-distance", as A. Einstein called it, were carried out only 30-35 years later, in the seventies-eighties \[3,4\]. Experimenterers, however, managed to achieve full and definite success only with photons (quanta of visible light), though, experiments with atoms \[5\] and protons (nuclei of hydrogen) were also performed \[6\]. For the case of photons, the experiments were carried out for various distances between the members of the EPR-pairs in the moment of registration. The EPR-correlation between the complementary photons was shown to survive up to as large distances as more than ten kilometers from one to another photon \[7\]. In the case of protons, the experiment was carried out only for much smaller distances (of about a few centimeters) and a condition of so-called causal separation, \[\Delta x > c\Delta t\], was not met. Thus, it was not fully convincing, as have been recognized by the authors of the work themselves.

**Teleporting photon-quantum state (or the light quantum itself?)**

A next step in this way that suggested itself was not merely "action-at-a-distance", but the teleportation at least of a quantum state from one quantum object to another. In spite of the successful experiments with the net EPR-effect, it was thought until recently that even this kind of teleportation is at best a long way in the future, if at all. At first sight it seems that the Heisenberg uncertainty principle forbids the first necessary step of the teleportation procedure: the extraction of complete information about the inner properties of the quantum object. This is because of the impossibility to obtain simultaneously the exact values of 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 \[8\]. They showed that full quantum information is not necessary for the process of transferring quantum states from one object to another which are at an arbitrary large distance from each other. Besides, they proposed that a so-called EPR-channel of communication has to be created on the basis of the EPR-pair of two quantum object (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 a "point of departure", where it meets A in a device (a registration system) arranged in a mode to "catch" only those events, in which B will appear in the state, leaving no choice to its "EPR-mate" but to take the state A had initially – before the 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. The conservation laws of general physics are the basis of the procedure realizing the system with a given selective sensitivity. A result of all these manipulations is that particle C gets something from A. It is only the quantum state. Unfortunately, not a soya bean, but all the same it is something. What

FIG. 1. Illustration of a general idea of how the teleportation can be realized. Here A is a light photon we want to pass to a destination place, B and C, representing an EPR-pair of photons, constitute a 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 photon with the properties A had just before it met intermediary object B ("vehicle"). Note that the vehicle first contacts with (so to say "visits") the C-photon to which the "cargo" has to be transported, and only later it calls A to take the cargo from it!
is important from the point of view of QM, is the disappearing of A in the place, notified in FIG. 1 as a "Zone of scanning" (ZS). That is, the procedure of interaction of B and A photons destroyed A photon, in a sense that of two photons outgoing from the ZS no one has definite properties of A. They constitute a new EPR-pair of photons, which only as a whole has the definite quantum state, the individual components of the pair are deprived of these properties. Thus, the photon A disappears at ZS. Exactly at the same moment the photon C obtains the properties A had in the beginning. Once it has happened, in view of the principle of identity of elementary particles, we can say that A, disappearing at ZS, reappears at another place, i.e., the 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 exchange of signals between A and C. And last, but not least of interest, in contrast to the transportation of ordinary material cargo, when a delivery vehicle first visits the sender to collect the cargo from it, in the case of cargo as subtle as quantum properties, it is delivered in a backward fashion. Here the photon B plays a role of the delivery vehicle, and we can see that B first visits (interacts with) the recipient (photon C) and only after that it travels to the sender (A) for the cargo.

Finally, to reconstruct initial object completely, it is necessary to fix a time moment when the interaction of A and B occurred (the moment of the arrival of the "vehicle" to the departure "station" after it visits the recipient), and accomplish the required experimental data processing in due manner. The task of recording the moment of (A-B)-interaction and using it in the data analysis together with the information transmitted by a quantum EPR-channel requires one more channel of communication, an ordinary or classical transmission line. Receiving information that A and B to form a new EPR-pair (using a classical telecommunication line), an observer in the point of destination may be sure that the properties of C are identical to those of A before the teleportation.

The new idea was immediately recognized as extremely important and a few groups of experimenters set forth concurrently to implement it. Nevertheless, it took more than four years to overcome all technology obstacles in the way to realize the project [9,10]. This is because every experiment in this field, being a record by itself, is always one step farther beyond the limits of experimental state of the art achieved before.

Start with protons

An analysis of the problem carried out by authors of the present experimental project which is now in a stage of preparation takes them to a conclusion that the experimental setups and instruments developed for usual, though the most modern, nuclear-physics studies (high-current accelerators of protons and heavier nuclei, liquid [12] and polarized [13] hydrogen targets, multi-parameter near $2\pi$-geometry – i.e. semi-spherical aperture – facility for particle detection named "Fobos" at Flerov Laboratory of Nuclear Reaction of the Joint Institute for Nuclear Research [11]), allow one to design a new way to perform the teleportation of the "heavy" matter (i.e., with non-zero mass at rest), with prospects to realize the project in a short time. Thus, the teleportation of the protons (nucleus of hydrogen atoms) could be achieved in about a year, and it would take about two years to
prepare the teleportation of more heavy nuclei, e.g., $^3$He. The concept of measurements consists in recording signals entering two independent but strictly synchronized memory devices with the aim to select afterwards only those events that for sure appeared to be causally separate, for even the most rapid signal (light) could not connect them. FIG. 2

![Diagram of proton teleportation](image)

**FIG. 2.** Layout of the experiments on proton teleportation. $p_0$ is an initial proton from the accelerator, LH$_2$ - liquid hydrogen target, $p_2$,$p_3$ - entangled EPR-pair, PH$_2$ - polarized hydrogen target, C - carbon target operating as an analyzer of the polarization of protons by a sign of scattering angle (left-right asymmetry), F-1 and F-2 - large-aperture position-sensitive particle detectors (so-called Fobos-facilities). Proton spin-state is being teleported from the PH$_2$-target placed at $x_0$ to the point $x_1$. It can be arranged that no signal from $x_0$ has enough time to reach point $x_1$ before $p_2$ obtains properties of $p_1$ at a moment $t_1$. That fact is justified by the detection system F-1/F-2 connected with a data-processing center by usual communication lines. K is a point, where the spin of $p_2$ gets a definite orientation: 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 $p_1$ loses its definite quantum state, as it forms a new EPR-pair together with the scattered proton $p_3$.

shows the layout of the experiment on teleportation of spin states of protons from a polarized target PH$_2$ into the point of destination (target C). A proton beam $p_0$ of a suitable energy within the 20-50 MeV range bombards the liquid-hydrogen target LH$_2$. According to the known experimental data, the scattering in the target LH$_2$ in the direction of a second target (i.e., at the c.m. angle $\theta \approx 90^\circ$) within a few percent occurs through a so-called singlet intermediary state, characterized by a zero total spin of the two-proton system. Thus, the outgoing $p_2$ and $p_3$ protons present a two-proton entangled system and are fully
analogous to the EPR-correlated photons used for transmitting information via the quantum communication channel in the experiments on the teleportation of "massless" matter (light photons), as it was discussed in the preceding section. One of the scattered protons, \( p_2 \), then travels to the point of destination (target-analyzer C), while the other, \( p_3 \), comes to a point where the teleportation is expected to be started, i.e., to the \( \text{PH}_2 \)-target. The latter is used as a source of particles we are going to teleport. In this sense, protons within this target play the same role as photons \( A \) in the above section. There are two features differentiating the case of protons from that of photons. First, protons \( p_1 \) are within the motionless target (and, thus, they are motionless themselves) where their density is greater; besides, the protons within the \( \text{PH}_2 \)-target have quite a definite quantum state, determined by a direction of polarization. The last circumstance allows one to perform the experiment under controllable conditions, i.e., this gives the possibility to check the expected result of the teleportation action. In the case when the scattering in the polarized target \( \text{PH}_2 \) occurs under the same kinematics conditions as in the target \( \text{LH}_2 \) (i.e., at the c.m. angle \( \theta \approx 90^\circ \)), the total spin of the particles \( p_1 \) and \( p_3 \) must also be equal to zero after collision. To detect these events, a removable circular module F-1 of the facility "Fobos" is supposed to be used, thus, the detection efficiency is hoped to be much enhanced. According to QM, if all the above conditions are provided, the protons reaching a point K suddenly receive the same spin projections as the protons in the polarized target \( \text{PH}_2 \) have. Therefore, the teleportation of the spin states from the \( \text{PH}_2 \)-target to the recipient \( p_2 \) really takes place at the point K. 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 target \( \text{PH}_2 \) and the direction of the deflection of \( p_2 \)-protons scattered in the carbon target C. C plays a role of the analyzer of polarization: the protons are deflected to the left or to the right depending on sign of their polarization, i.e., the orientation of the proton spin that can have only two alternatives (along or opposite to a given direction \([14]\)). The second module of "Fobos", designated F-2 in the FIG. 2, crowns the procedure of teleportation, as it indicates the proton scattering direction in the carbon target C, and hence, its polarization.

If we succeeded to make a distance between the detectors F-1 and F-2 to be sufficiently large, then it would be possible to meet the important criteria of the space-like interval (causal independence) between the events of the "departure" of the quantum state from the \( \text{PH}_2 \)-target and "arrival" of this "cargo" to the recipient (\( p_2 \)-proton) at the point K. To prevent any exchange of signals between the points \( \text{PH}_2 \) and K, it is essential to choose appropriate proportions of some time and space segments, indicated in FIG.2. Namely, we have to obtain \( S > c t_{12} \), where \( t_{12} = |t_{F1} - t_{F2}| \). Here \( t_{F1} \) and \( t_{F2} \) are moments of registration of signals from the corresponding detectors F-1 and F-2 (their arrival at the data collection-processing center). For simplicity, we neglected a time of flight of the protons from K to C, and from the \( \text{PH}_2 \)- and C-targets to the detectors F-1 and F-2, respectively.

**Conclusion**

Finally, referring to the principle of identity of elementary particles of the same kind with the same quantum characteristics, i.e. the protons in our case, we can say that protons from a polarized target \( \text{PH}_2 \) 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 physicists’ laboratories.

Remembering that the above soybeans contains not only protons but as well proteins, somebody perhaps feels disillusioned. However, we should not be stingy, something should be left for physics of the third millennium.

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[1] A. Einstein, B. Podolsky, and N. Rosen, Can Quantum-Mechanical Description of Physical Reality be Considered Complete? Physical Review 41, 777 (1935).
[2] N. Bohr, Can Quantum-Mechanical Description of Physical Reality be Considered Complete? Physical Review 48, 696 (1935).
[3] A. Aspect, J. Dalibard, G. Roger, Experimental Test of Bell’s Inequalities Using Time-Varying Analyzers, Phys. Rev. Lett., Vol.49, No.25 1804 (1982).
[4] J.F. Clauser, A. Shimony, Bell’s Theorem: Experimental Tests and Implications, Rep. Prog. Phys., 41, 1881 (1978).
[5] E. Hagley, X. Maitre, G. Nogues, C. Wunderlich, M. Brune, J.M. Raimond, and S. Haroche, Generation of Einstein-Podolsky-Rosen Pairs of Atoms, Phys. Rev. Lett. 79, 1 (1997).
[6] M. Lamehi-Rachti and W. Mittig, Quantum Mechanics and Hidden Variables: A Test of Bell’s Inequality by the Measurement of the Spin Correlation in Low-Energy Proton-Proton Scattering, Phys. Rev. D, Vol. 14, No. 10 2543 (1976).
[7] W. Tittel, J. Brendel, H. Zbinden, N. Gisin, Violation of Bell Inequalities by Photons More than 10 km Apart, Phys. Rev. Lett., Vol. 81, No. 17 3563 (1998).
[8] C. H. Bennett, G. Brassard, C. Crepeau, R. Jozsa, A. Peres, and W.K. Wooters, Teleporting an Unknown Quantum State via Dual Classical and Einstein-Podolsky-Rosen Channels, Phys. Rev. Lett. 70, 1895 (1993).
[9] D. Bauwmeester, J. W. Pan, K. Mattle, M. Eibl, H. Weinfurter, and A. Zeilinger, Experimental quantum teleportation, Nature, Vol. 390 575 (1997).
[10] D. Boschi, S. Branca, F. De Martini, L. Hardy, and S. Popescu, Experimental Realization of Teleporting an Unknown Pure Quantum State via Dual Classical and Einstein-Podolsky-Rosen Channels, Physical Review Letters, Vol. 80 No. 6 1121 (1998).
[11] H.-G. Ortlepp et al., FOBOS Collaboration, Scientific Report 1995/1996 Heavy Ion Physics, B. I. Pustylnik (Ed.), JINR E7-97-206 JINR Dubna, Russia, p. 236.
[12] M. A. van Uden, R. L. J. van der Meer, Th.S. Bauer, M. Bron, R. Buis, P.J.M. de Groen, Y. Lefèvre, G. J. L. Nooren, H. Postma, G. van der Steenhoven, H. W. Willering, The HARP Liquid Hydrogen System, Nuclear Instruments And Methods In Physics Research Sect. A Vol. 424 No.2-3 580 (1999).
[13] D.J. Crabb and W. Meyer, Solid Polarized Targets for Nuclear and Particle Physics Experiments, Annu. Rev. Nucl. Part., Sci., 47, 67 (1997).
[14] C. Tschalär, C. J. Batty and A.I. Kilvington, A Polarization Analyzer for 40- to 50-MeV Protons, Nuclear Instruments and Methods, Vol. 78 141 (1970).