QUANTUM TELEPORTATION OF NUCLEAR MATTER AND ITS INVESTIGATION

V. V. Ivanov [a], *B. F. Kostenko* [a,1], *V. D. Kuznetsov* [a], *M. B. Miller* [b], *A. V. Sermyagin* [b]

[a] Joint Institute for Nuclear Research, Dubna
[b] Institute of Physical and Technology Problems, Dubna, Russia

Since its discovery in 1993, quantum teleportation (QT) is a subject for intense theoretical and experimental studies. Experimental demonstration of QT has so far been limited to teleportation of light. In this paper, we propose a new experimental scheme for QT of nuclear matter. We show that the standard technique of nuclear physics experiment could be successfully applied for teleportation of spin states of atomic nuclei. We claim that there are no theoretical prohibitions upon a possibility of a complete Bell measurement, therefore, the implementation of all the four quantum communication channels is at least theoretically possible. A general expression for scattering amplitude of two $1/2$-spin particles is given in the Bell operator basis, and the peculiarities of Bell states registration are briefly discussed.

INTRODUCTION

Since its discovery in 1993, quantum teleportation (QT) is a subject of intensive theoretical and experimental studies [1]. If quantum computers will be really constructed, QT is expected to have a great influence on a future computation and communication hardware, presumably comparable with the impact of the radio network on modern technique. This is because the practical realization of quantum information processing requires special quantum gates which cannot be performed through unitary operations, but may be constructed if one uses quantum teleportation as a basis primitive. Another important application of QT is a secure data transmission in a so-called quantum cryptography [2, 3].

Besides a relevancy to the applications, QT presents also a new fundamental concept in quantum physics. Indeed, the very phenomenon of QT is based on Einstein–Podolsky–Rosen correlations, which have been correctly confirmed only for photons. The same is true for QT — only the entangled optical beams have been used to teleport quantum states up to now [4, 5].

As far as the quantum information processing involves material particles with nonzero mass, teleportation of heavy matter is considered now to be the next important landmark on the way to obtain a complete set of quantum computation tools [6–8]. We propose here a new experimental scheme for QT of heavy matter states, which is based on the standard techniques of nuclear physics experiment and may be fulfilled in the next one or two years. To the best of our knowledge, other proposals require much more time for their implementation.

[1] Corresponding author. Laboratory of Information Technologies, Joint Institute for Nuclear Research, 141980, Dubna, Russia. Tel.: +007-096-21-64-069; fax: +007-096-21-65-145. e-mail: kostenko@jinr.ru (B. F. Kostenko).

1. BASIC IDEAS

The first experimental demonstration of photon state teleportation had a great public resonance and was even elucidated in mass media. Indeed, not long ago only science-fiction authors ventured to use this term. Although no materials, but only quantum states, were really transmitted in those experiments, in fact, journalists were not very far from the truth using the term in the same sense as the science-fiction authors. If one takes into account the indistinguishableness of elementary particles of the same sort, the photons in our case, one can say that interchange of distant photon states is nothing else but teleportation of the matter itself.

It is slightly more difficult to explain why the experiments mentioned above had produced a big impression on the specialists as well. The fact is that just not long before a no-cloning theorem for quantum states has been proved [9]. It states that it is not possible to construct a device that produces an exact copy of an arbitrary quantum system. This result forbids to use the methods of information copying technique traditionally employed for classical computers. The theorem was accepted as a serious obstacle encountered on the way of quantum computer elaboration. At that time nobody knew with certainty if it is possible to organize somehow the communication between different parts of a quantum computer, or the very idea of quantum information processing is quite wrong.

The solution of the problem, very simple and amazing, was given in [1]. The idea can be explained as follows. Let us consider a quantum system consisting of three particles with half-integer spins and let us suggest that one of the particles is in the state

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

to be teleported. If the residuary two particles were prepared in the entangled state with zero total spin

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

the state vector of the considered three-particle system is

$$|\Psi_{123}\rangle = |\phi_1\rangle|\Psi_{23}\rangle.$$

Using a so-called Bell's basis,

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

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

the state of three-particle system can be identically rewritten in the form

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

Now, let us assume that the observer succeeds in fulfilling the measurements discriminating different Bell's states for the system consisting of particles 1 and 3. Then carrying out such a measurement and knowing the result, he will know certainly the state of the particle 2. Namely, in accordance with the modern quantum theory, the following correspondence should take place:

$$
\begin{aligned}
|\Psi_{13}^{(-)}\rangle &\longrightarrow a|\uparrow_2\rangle + b|\downarrow_2\rangle,\\
|\Psi_{13}^{(+)}\rangle &\longrightarrow a|\uparrow_2\rangle - b|\downarrow_2\rangle,\\
|\Phi_{13}^{(-)}\rangle &\longrightarrow -a|\downarrow_2\rangle - b|\uparrow_2\rangle,\\
|\Phi_{13}^{(+)}\rangle &\longrightarrow -a|\downarrow_2\rangle + b|\uparrow_2\rangle.
\end{aligned}
$$

The first of the above-mentioned states of particle 2 exactly coincides with the state that particle 1 possessed before the measurement. Thus, in this case, teleportation of the given quantum state is totally completed. For three other cases, three different unitary operations should be additionally performed to transform the obtained state of particle 2 into the required one. They could be accomplished either over particle 2, or over the observer's laboratory itself, but in both cases they are ordinary rotations[1].

The most important from the principal point of view is «disappearing» of the individual particle 1 in the place, which could be notified as «zone of scanning» (ZS), where the measurement preparing particles 1 and 3 in one of Bell's states is accomplished. Indeed, this measurement destroys the particle 1, in a sense that none of the two particles outgoing from ZS has definite properties of the particle 1. They constitute a new pair of particles, 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 particle 1 really disappears at ZS. Exactly at the same moment, the particle 2 obtains the properties particle 1 had in the beginning. Once it has happened, in view of the identity principle of elementary particles, we can say that the particle 1, disappearing at ZS, reappears at another location. Thus, quantum teleportation is accomplished. It can be seen as well that the no-cloning theorem is not violated.

QT has several paradoxical features. In spite of the absence of contacts between objects (particles, photons) 1 and 2, 1 manages to pass its properties to 2. It may be arranged in such a way that the distance from 1 to 2 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 proton 3 plays a role of the delivery vehicle, and one can see that 3 first interacts with the recipient 2, to prepare the entangled state $|\psi_{23}\rangle$, and only after that it travels to the sender (1) for the «cargo».

Finally, to reconstruct the 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 the quantum signal (incoming with the particle 2) 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 1 and 3 form a new EPR-pair with zero total spin, an observer at destination may be sure that the

[1]Taking into account that orthogonal vectors in the spinor space correspond to oppositely oriented projections of spin in the usual one, it is easy to understand that the rotation angle of the laboratory is twice as many the angle of the spinor unitary operation for $|\phi_2\rangle$.

properties of 2 are identical to those of 1 before the teleportation. In the case when 1 + 3 system has nonzero total spin, additional transformation of quantum signal is needed.

2. LAYOUT OF AN EXPERIMENT

One can convert the previous formulas into a concrete experimental layout for proton teleportation. In Fig. 1, the layout of an experiment on teleportation of spin states of protons from a polarized target, PH_2, into the point of destination (target C) is shown.

A proton beam p_0 of the suitable energy within the range 20–50 MeV bombards a liquid hydrogen target, LH_2 (which may be also replaced by an ordinary polyethylene foil). According to the known experimental data, the scattering in the LH_2 target corresponding to the scattering angle $\theta \simeq 90°$ at the c. m. s. occurs within an acceptable accuracy through the singlet intermediary state [10]. Thus, the outgoing protons p_2 and p_3 form a two-proton entangled system in the state $|\Psi_{23}\rangle$ that was introduced in the preceding section. One of the scattered protons, p_2, then travels to the destination point (the target-analyzer C), while the other, p_3, arrives to the point where teleportation is started, i. e., to the PH_2 target. The last one is used as a source of teleportated particles which have quite definite quantum state

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

determined by a direction of polarization. This direction could be chosen accidentally and, thus, unknown to the experimenters. In the case when scattering in the polarized PH_2 target occurs under the same kinematic conditions as in the LH_2 target (i. e., at the c. m. s. scattering angle $\theta \simeq 90°$), the total spin of the particles p_1 and p_3 must also be equal to zero after collision, and they find themselves in the state $|\Psi_{13}^{(-)}\rangle$. To detect the events, a removable circular modules F-1 and F-2 (e. g., of the facility «Fobos») could be used[1]. If all the above conditions are provided, the protons reaching the point K will suddenly receive the same spin projections as the protons in the polarized PH_2 target.

Thus, if the coincidence mode of the detection of $|\Psi_{13}^{(-)}\rangle$ state is provided via any classical channel shown in Fig. 1, 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

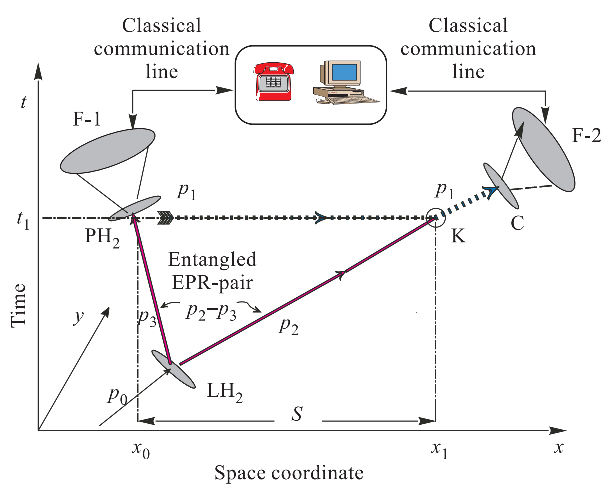

Fig. 1. Experiment on proton state teleporation

[1]The 4π spectrometer FOBOS is a setup at the Flerov Laboratory of Nuclear Reactions of JINR.

target C[1]. Therefore, at least for those events when particles 1 and 3 are registered to be in the state $|\Psi_{13}^{(-)}\rangle$, teleportation of protons could be experimentally fulfilled.

Besides, 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 criterion of the causal independence between the events of the «departure» of the quantum state from PH_2 target and the «arrival» of this «cargo» to the recipient (proton p_2) at the point K. This kind of measurements consists in recording signals entering two independent but strictly synchronized memory devices with the aim to select afterwards those events alone that appeared to be causally separated. Thus, the experimental setup shown in Fig. 1 also allows one, at least in principle, to fill the gap in the verification of the EPR-effect for heavy matter.

3. MORE EFFECTIVE EQUIPMENT FOR PROTON TELEPORTATION

In fact, it is possible to increase essentially the rate of teleportation, mainly due to the extension of the solid registration angle, if one makes use of another layout of experiment, shown in Fig. 2. In the figure, protons P_0 from the primary beam incident onto a hydrogen target T_1 (polyethylene) and undergo the interaction which results in arising of two protons traveling toward targets T_2 and T_3. These ones are located in such a way that only the protons with scattering angles of about 90° at c. m. s. (or nearly of 45° in the laboratory system) arrive at them both.

Under this condition, P_1 and P_0' should have the entangled quantum state with zero total spin value (i. e., they constitute the EPR-pair). T_2 is the polarized target analogous to that mentioned in the previous section. T_3 represents the analyzer for protons P_0', and it may be the carbon foil as well as another hydrogen polarized target. In the case displayed in picture, one more polarized target is used for this purpose.

A new entangled two-particle state with zero total spin value can be knocked out as a result of proton–proton scattering within T_2. The registration of proton in the detector D_1, selecting the scattering angles in the vicinity of 45° l. s., should be the signature for this event. In that case, in accordance with the general idea of teleportation, «Alice» (the signal sender) must inform «Bob» (the receiver) that the quantum communication channel Ψ^- has been realized. A similar information about proton detection in the D_2 indicates the fact of preparation of another two-particle state with the spin value $S = 1$ and spin projection $S_z = 0$. Accordingly, the Ψ^+ communication channel will be formed in the left shoulder of the layout.

The existence of proton state teleportation can be easily proved by measuring the proton cross section in the polarized target T_3. If teleportation takes place, indeed, protons P_0' should be polarized, too, and this fact could be checked due to the dependence of nuclear cross section on the polarization of scattering particles.

Contrary to the idea of teleportation, proposed by C. Bennett et al. [1], the spatial separation of different quantum channels in the present layout allows Bob to control the value of the

[1]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 [10].

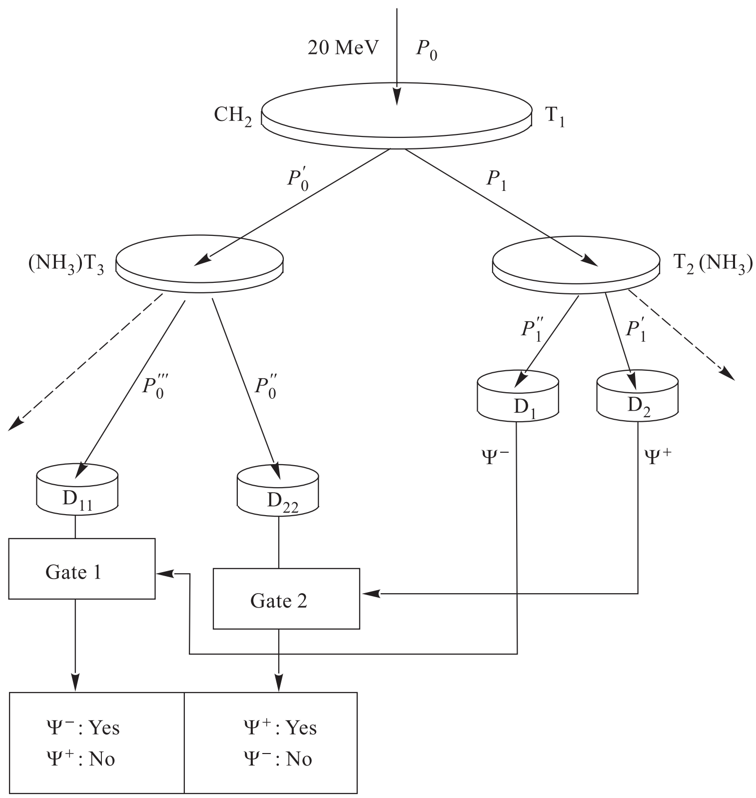

Fig. 2. Layout of a more effective experiment

teleported polarization by means of the Renninger-type measurements [11], i. e., without any perturbation of the teleported state. Thus, the information on the signal presence in the D_1 detector in conjunction with the absence of the signal in the detector D_{22} makes Bob to be sure that the teleported particle has the same polarization as that of protons within the T_2 target. The conjunction could be organized as follows: when the signals from the D_1 and D_2 detectors enter controlling inputs of gate-units, Gate 1 and Gate 2, the reciprocal signals arise at the output of these gates corresponding to the realization of different Bell's states (indicated in the table seen at the bottom of Fig. 2)[1].

It is interesting to note that from classical physics viewpoint the target T_3 should be located lower than it is shown in the figure, in order the protons P_0' to incident onto it only after the complementary proton P_1'' of the EPR-pair is detected within the D_1 detector. From

[1]It is worth noting that the represented layout is set specially for the experimental verification of possibility of the quantum state teleportation for heavy matter. In the case of «practical application» of quantum teleportation, neither the analyzer T_3, nor the detectors D_{11}, D_{22} are necessary. What remains essential is to transmit from the Alice location to the Bob one, via the classical communication channel, the information about the results of measurements in the right side of the layout.

a naive point of view, only after that protons P_0' acquire a certain state of spin. Nevertheless, according to the Copenhagen interpretation, no event can be considered existing until it is detected (by D_{11} and D_{22} in the case under consideration); the displayed dislocation of the targets is possible as well.

A real polarized target, which permits one to carry out the above-considered experiment, is described in the Appendix.

4. BELL OPERATOR BASIS

In the experiments that were carried out up to now, only one quantum channel corresponding to the registration of Bell's state $|\Psi_{13}^{(-)}\rangle$ has been used. In this connection, the question arises as to whether it is possible to involve other channels correlating with the states $|\Psi_{13}^{(+)}\rangle$, $|\Phi_{13}^{(-)}\rangle$ and $|\Phi_{13}^{(+)}\rangle$.

To answer this question, let us consider the general expression for the scattering amplitude of two particles, not necessarily identical ones, with the spin value $1/2$,

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

Using a relation

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

in the case of the coordinate system to be fixed 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

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

It can be shown that the scattering operator $\hat{f}$ can be now expressed through the Bell transition operators by making use of the 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 the 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

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

In the case $E = F = 0$, the expression (1) is the usual spectral decomposition for the operator $\hat{f}$ that allows one to interpret $\hat{f}$ as an operator of some quantum observable. Therefore, to register a definite Bell 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 the registration of each Bell's state is possible at least theoretically.

The 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. This 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 the normalized orthogonal states with the definite values of 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 $\pi/2$, 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 the $|\Psi^{(+)}\rangle$ state also opens the way to register two other states $|\Phi^{(+)}\rangle$, $|\Phi^{(-)}\rangle$ by means of change to $\pi/2$ of the direction along which the spin projection is measured.

For identical spin 1/2 particles the scattering operator (1) has some additional symmetries, so that in c. m. s. one has

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

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

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

The 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 the spin projection measurement for particles 1 and 3 is

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

for any choice of the 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 $S_{z1} = 1/2$ and $S_{z3} = 1/2$ or $S_{z1} = -1/2$ and $S_{z3} = -1/2$ with the same probability $p = 0.5$. Now the measurement of the spin projection of the particle 2 allows one to determine which of two possible states, $|\Phi_{13}^{(-)}\rangle$ or $|\Phi_{13}^{(+)}\rangle$, the scattering has really occurred into.

CONCLUSION

In recent years, there has been an explosive growth in new experimental techniques that can be adapted in future quantum computers and communication channels. Among them are: neutron and electron interferometry, photon down-conversion in nonlinear crystals, special ultrafast lasers and micromasers that can create few-photon states, trapping of individual atoms, atomic interferometry, Josephson tunnel junctions, cavity quantum electrodynamics, quantum dots in solids, etc. Some of these results are now used to test quantum theory itself for the purpose of determining its limits and for the verification of the alternative interpretations of quantum mechanics which have been developed instead of the traditional Copenhagen one over the years.

The proposed technique of quantum teleportation is the first one which suggests to use methods of nuclear physics including nucleon–nucleon scattering and appropriate methods of event registration. The project presented in this paper has the following nearest objectives:

- Experimental setup for realization of nuclear teleportation.
- Experimental proof of quantum teleportation phenomenon for nuclear matter over $\Psi^{(-)}$ Bell's information transmission channels.
- Theoretical and experimental proof of possibility of other ways of quantum information transmission for nuclear matter states, in particular, using $\Psi^{(+)}$ transmission channel.

Although each novel way of quantum state engineering with single heavy particles is valuable itself, we point out some distinguished properties of this approach. The first preference concerns the rate of teleportation. Our estimations show that the present nuclear physics experimental device allows one to teleport at least 10^5 protons per second without any additional refinements. Another peculiarity of the method is very small space–time region of event localization — inside the atomic nuclei. These advantages may be useful not only in the future quantum computers, but also for investigations of some theoretical puzzles today. The most intriguing of them are: how and when does the modern theory of quantum measurements break down (presumably somewhere in the middle between micro- and macrolevel), has the environment-induced wave packet collapse any sense, or is presence of the observer's mind necessary, indeed?

Among future objectives of the project, one may point out the following:

• A test of Bell's inequalities by the measurement of the spin correlations in low-energy proton–proton scattering, which meets the requirement of space-like character for the intervals between the successive events of proton spin projection measurements.

• Measurements of the wave packet collapse duration and its spatial localization with a maximally possible precision. Practically, this objective may be achieved by maximal increase of teleportation rate and decrease of size of the teleporting equipment.

Acknowledgements. We are grateful to Prof. I. Antoniou (Solvay Institutes for Physics and Chemistry, Brussels), Prof. V. V. Belokurov and Prof. O. A. Khrustalev (Moscow State University) for helpful discussions and support. Our special gratitude to Dr. Yu. F. Kiselev (Joint Institute for Nuclear Research, Dubna) who provided us the Appendix. One of us (B. F. K.) acknowledges the financial support of the Russian Foundation for Basic Research, project No. 02-01-00606.

Appendix
POLARIZED HYDROGEN TARGET

At present, two types of solid polarized nuclear targets exist, which differ as to the type of refrigerator used for their cooling. Namely:

1. Targets with refrigerator of evaporator type with ^{3}He or ^{4}He.
2. Targets of frozen type with the dissolution of ^{3}He in ^{4}He.

Targets of the first type operate at temperatures 0.3–1.2 K. Their evaporation cycle of cooling allows one to attain the greater rate of the cold generation (up to 20–50 J/mol), so that the targets are resistant to the greater particle intensity (up to 10^{11} pps). They are distinguished by a high reverse velocity of polarization (depending on temperatures of the cooling agent). With the account of conditions of the teleportation experiment, the best variant of the target scheme is the American installation E143 (SLAC). In this scheme, a leakage of nuclear polarization is reduced not by the temperature lowering, but by means of increasing the magnetic field up to 5 T. As a result, when operating with ammonia NH_3 and liquid ^{4}He, the authors of the method managed to reach a remarkable result: 90 % polarization of the protons under a specific RF-power of the order of 12 mW/cm^3.

As it has been in the original construction, our evaporation refrigerator is supposed to contain a wide-aperture magnet from two or three pairs of superconducting Helmholtz coils (see Fig. 3), intended for getting a magnetic field of necessary homogeneity on targets with diameter and length of about 30 mm. The refrigerator represents an ordinary helium cryostat (4.2 K) for a magnet of that type the Oxford Instruments Company (OIK) produces. In the area of the nuclear target, a temperature of about 1 K could be provided with the use of a rather simple cooling plunger. In the case of thin nuclear targets, the requirements on

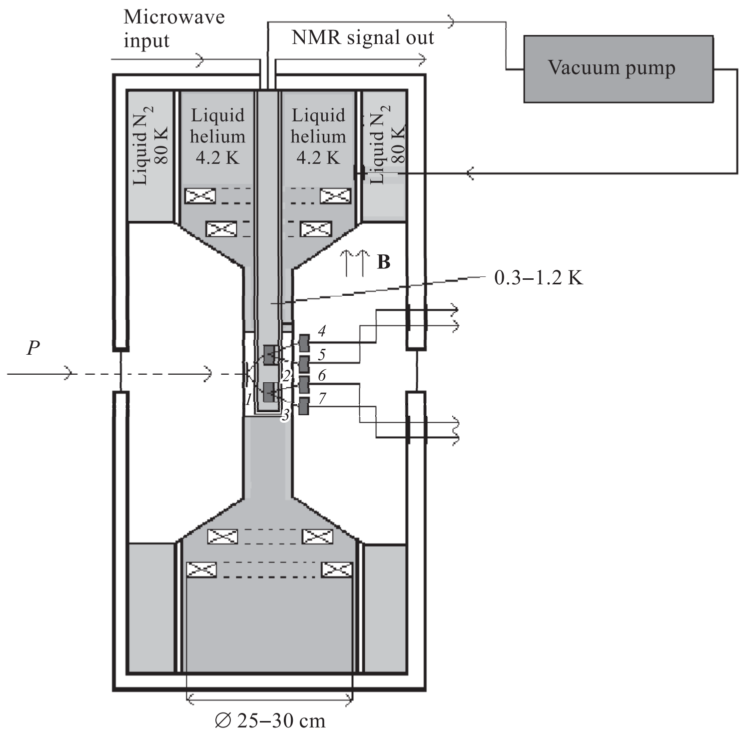

Fig. 3. Low-temperature refrigerator with nuclear targets and particle detectors: *1* — primary hydrogen target; *2, 3* — nuclear hydrogen polarized targets; *4, 5, 6, 7* — particle detectors (D_1, D_2, D_{11} and D_{22} from Fig. 2)

homogeneity are not very strict. Preliminary negotiations with OIC have displayed that the magnet could even be of a more simple design.

Contrary to the standard E143 device, it is planned to implement the circulation contour (of the type used in the frozen targets). This innovation has to allow cooling of the target with ^{4}He as well as with ^{3}He, and this, in turn, allows one to achieve a very high polarization, practically nearly 100 %.

The arrangement of primary hydrogen target and polarized targets (which were shown above in Fig. 2) in the low-temperature refrigerator is depicted in Fig. 3.

REFERENCES

1. *Bennett C. H. et al.* // Phys. Rev. Lett. 1993. V. 70. P. 1895.
2. *Dentsch D.* // Phys. World. 1993. V. 6. P. 22.
3. *Ekert A. K. et al.* // Phys. Rev. A. 1994. V. 50. P. 1047.
4. *Bauwmeester D. et al.* // Nature. 1997. V. 390. P. 575.

5. *Boschi D. et al.* // Phys. Rev. Lett. 1998. V. 80. P. 1121.
6. *Kuzmich A., Polzik E. S.* Atomic Quantum State Teleportation and Swapping. quant-ph/0003015.
7. *Maierle C. S., Lider A., Harris R. A.* // Phys. Rev. Lett. 1998. V. 81. P. 5928.
8. *Parkins A. S., Kimble H. J.* // J. Opt. B. 1999. V. 1. P. 4967.
9. *Wooters W. K., Zurek W. H.* // Nature (London). 1982. V. 299. P. 802.
10. *Lamehi-Rachti M., Mittig W.* // Phys. Rev. D. 1976. V. 14. P. 2543–2555.
11. *Jammer M.* The Philosophy of Quantum Mechanics. N. Y.: J. Wiley & Sons, 1974. P. 495.