Preliminary results of the Baikal experiment on observations of macroscopic nonlocal correlations in reverse time

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Macroscopic quantum entanglement is intriguing phenomenon, the theory of which is still in its infancy. Heuristic consideration of the matter in the framework of action-at-a distance electrodynamics predicts for some processes observability of the advanced nonlocal correlations (time reversal causality). For diffusion entanglement swapping the effective time shifts can be very large. These correlations with greater magnitude than usual retarded ones were really revealed in our previous experiments. Moreover the possibility of the forecast of large-scale heliogeophysical random processes on macroscopic nonlocal correlations had been proven. However the laboratory experiment is difficult because of problem of nonlocal correlation detector shielding against the classical local impacts. Since 2012 a new experiment has been performing on the base of Baikal Deep Water Neutrino Observatory. The thick water layer is an excellent shield against any local impacts on the detectors. A couple of nonlocal correlation detectors, measuring spontaneous variations of self-potential difference between weakly polarized electrode pair, were installed at the depths 52 and 1216 *m*. The bottom detector works under conditions of perfect thermostating and stability of all other environment parameters. Any classical correlations between top and bottom detector signals are impossible. Processing of the first annual time series has revealed rather strong correlation between the signals of bottom, top and spaced at 4200 *km* laboratory detector in Troitsk. The detectors respond to the external (heliogeophysical) processes, and the signal causal connection, revealed by causal analysis turned out directed downwards – from the Earth surface to Baikal floor. But this nonlocal connection proved to be in reverse time – the bottom detector responds earlier than the top one, and top one earlier than surface one. Another result is uncovered nonlocal correlation of the detector signal with a regional source-process – the variation of subsurface (22 *m*) temperature. The temperature is a cause with respect to detector signal, but this nonlocal causal connection is time reversal. The possibility of the temperature forecast with advancement 45 days has been demonstrated.

Introduction

Widely discussed in the past apparent violation of relativity in the entangled states is quite understood now in the framework of quantum nonlocality. Instantaneous and even advanced correlations are possible namely due to absence of any local carriers of interaction. In turn, advanced correlations can occur not only through a space-like interval that could mean usual reversal of time ordering of causally unconnected events. According to the principle of weak causality [1], for the unknown quantum states (or, in other terms, for the random processes) advanced correlations through a time-like interval and hence time reversal causality are possible too. Recently this possibility has been proven experimentally for quantum teleportation [2, 3] and entanglement swapping [4, 5]. Most theoretical efforts in this area are focused on the entanglement of a few microscopic particles. On the other hand, the problem of macroscopic entanglement attracts increasing attention. Macroscopic quantum entanglement is intriguing phenomenon, the theory of which is still in its infancy. But one of the important results of the progress in quantum information theory was discovery of constructive role of dissipation in entanglement generation [6-13]. It bridges the recent research with the early works of Kozyrev, who likely was the first to observe macroscopic entanglement of the dissipative processes with time reversal causality [14, 15].

Background

Our idea was to include dissipation in the framework of Cramer interpretation of quantum nonlocality by Wheeler-Feynman action-at-a-distance electrodynamics [1, 16]. This theory considers the direct particle field as superposition of the retarded and advanced ones. The advanced field is unobservable and manifests itself only via radiation damping, which can be related with the entropy production [17, 18]. Any dissipative process is ultimately related with the radiation damping and therefore the advanced field connects the dissipative processes.

The following heuristic equation of macroscopic entanglement was suggested and tested [17, 23]:

$$\dot{S}_d = \sigma \int \frac{\dot{s}}{x} \delta\left(v^2 t^2 - x^2 \right) dV , \tag{2.1}$$

where $\dot{S}_d$ is the entropy production per particle in a probe process (that is a detector), $\dot{s}$ is the density of total entropy production in the sources, the integral is taken over the source volume, σ is cross-section of transaction (it is of an atom order and goes to zero in the classical limit): $\sigma \approx \hbar^4 / m_e^2 e^4$, m_e is the electron mass, e is the elementary charge. The δ-function shows that transaction occurs with symmetrical retardation and advancement. The propagation velocity v for diffusion entanglement swapping can be very small. Accordingly, the retardation and advancement can be very large.

But it should be noted that our equation in its simplest form does not take into account the absorption by the intermediate medium. Its influence, however, is very peculiar. Although the equations of action-at-a-distance electrodynamics are time symmetric, the fundamental time asymmetry is represented by the absorption efficiency asymmetry: the absorption of retarded field is perfect, while the absorption of advanced one must be imperfect [18, 22, 24, 25]. It leads to the fact, that level of advanced correlation through a screening medium may exceed the retarded one.

The experimental problem is to establish correlation between the entropy variations in the probe- and source-processes, according to Eq. (2.1) under condition of suppression of all classical local impacts. The detector based on spontaneous variations of self-potentials of weakly polarized electrodes in an electrolyte proved to be the most reliable one [17-21]. The theory of the electrode detector starts from self-consistent solution of the entropy production in the liquid phase. The entropy of distribution can be expressed in terms of full contact potential. From here one can get the expression of the entropy variation in terms of potential difference between a couple of electrodes, which is the detector signal [17-22].

All known local impacts influencing the detector signal, namely, temperature, pressure, electric field, etc. must be excluded technically and mathematically, which is rather difficult problem.

In our previous works we had conducted a number of the long-term experiments [17-23, 25-29]. Shortly, we revealed macroscopic nonlocal correlations, on the one hand, between the different detectors spaced up to 40 *km*, and, on the other hand, between them and some large-scale astrophysical and geophysical dissipative processes with big random component. Nonlocal nature of correlation had been proven by violation of Bell-like inequality. The most prominent fact was reliable detection of advanced correlations and experimental proof of time reversal causality for the random processes.

The mathematical tool for this proof is causal analysis, which recently plays also important role in theoretical studies of quantum information problems [18, 30-32]. As a matter of fact, although the considered phenomenon is quantum, but as we deal with the classical output of measuring device, we can use simpler classical causal analysis. Recall some points [18-33]. For any variables X and Y several parameters can be defined in terms of Shannon marginal $S(X)$, $S(Y)$ and conditional $S(X|Y)$, $S(Y|X)$ entropies. The most important are the independence functions:

$$i_{Y|X} = \frac{S(Y\,|\,X)}{S(Y)},\ i_{X|Y} = \frac{S(X\,|\,Y)}{S(X)},\ 0 \le i \le 1. \tag{2.2}$$

Next the causality function γ is considered:

$$\gamma = \frac{i_{Y|X}}{i_{X|Y}},\ 0 \le \gamma < \infty, \tag{2.3}$$

We can define that X is the cause and Y is the effect if $\gamma<1$. And inversely, Y is the cause and X is the effect of $\gamma>1$. In the quasiclassical domain that is at positive conditional entropies the measure of causality γ and quantum measure called the course of time (c_2) [18,30-32] are equivalent, in this paper we prefer use γ because of its simplicity. In terms of γ the principle of classical causality is formulated as follows:

$$\gamma < 1 \Rightarrow \tau > 0,\ \gamma > 1 \Rightarrow \tau < 0,\ \gamma \to 1 \Rightarrow \tau \to 0\,, \tag{2.4}$$

where τ is time shift of Y relative to X.

On theoretical and plenty of experimental examples it had been shown that such a formal approach to causality did not contradict its intuitive understanding e.g. [33-37]. Only in case of nonlocal correlation one can observe violation of this principle. In our previous experiments such time reversal causality had given us even the possibility of successful forecasting of the large-scale heliogeophysical processes [17, 18, 21-29].

Experiment

Since 2012 a new experiment has been performing on the base of Baikal Deep Water Neutrino Observatory. Baikal is the deepest lake in the World and its thick water layer is an excellent shield against the classical local impacts. In particular, the temperature near the floor is constant up to 0.01 *K*.

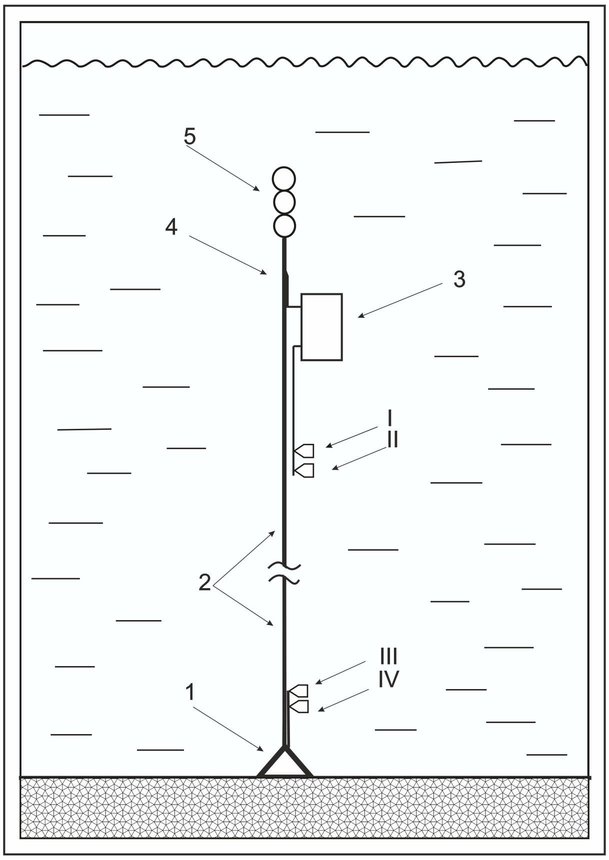

Fig. 1: Baikal Deep Water Setup (1 – anchor; 2 – cable; 3 – electronics unit, acceleration and temperature sensors; 4 – buoy rope; 5 – buoy; I, II – top electrode detector; III, IV – bottom electrode detector).

The experiment aims, first, study of nonlocal correlation between the detectors at different horizons in the lake and spaced at 4200 *km* lab detector in Troitsk, and second, study of correlations of detector signals with the global and regional source-processes.

In Fig.1 the scheme of Baikal Deep Water Setup is shown. The site depth is 1367 *m*. The bottom detector is set at the depth 1216 *m*, the top one is set at the depth 52 *m*. Both the detectors represent a couple of high quality weakly polarized *AgClAg* electrodes HD-5.519.00 with practically zero separation. These electrodes were originally designed for high precision measurements of the weak electric fields in the ocean, and they are best in the World by their self-potential insensitivity to the environmental conditions.

The signal are measured and stored in the electronics unit set at the depth 22 *m*. The sampling rate is 10 *s*. The calibration and zero control are done automatically daily. The relative error of measurements is less than 0.01%. In addition, the electronics unit contains the temperature and acceleration sensors. The setup is fixed by the heavy anchor on the floor and by the drowned buoy at the depth 15 *m*.

The setup is designed to be operated autonomically for a year. It was installed from the ice in March, 2012. In March, 2013 the setup was lifted on the ice for data reading and battery changing and then it was installed again for the next year.

It is known that the strongest macroscopic nonlocal correlations are observed at extremely low frequencies, that is at periods of several months. Therefore our experiment is planed for several years.

Preliminary results of the first annual series

So from classical point of view the detector signals must be uncorrelated random noises. But it is not the case. In Fig. 2 the normalized amplitude spectra of the bottom detector U_b , top one U_t and far distant Troitsk lab one U_l are presented. The period range is from 10 to 220 days. It is seen that at the longest periods the spectra are similar. We observe the semiannual variation, about 100-days solar intermittent variation [38] and its second harmonic, the split maxima around period of solar rotation and its second and third harmonics. The longer period, the better spectra similarity. It is also seen that spectrum of U_b more exactly corresponds to close U_t one than to distant U_b one.

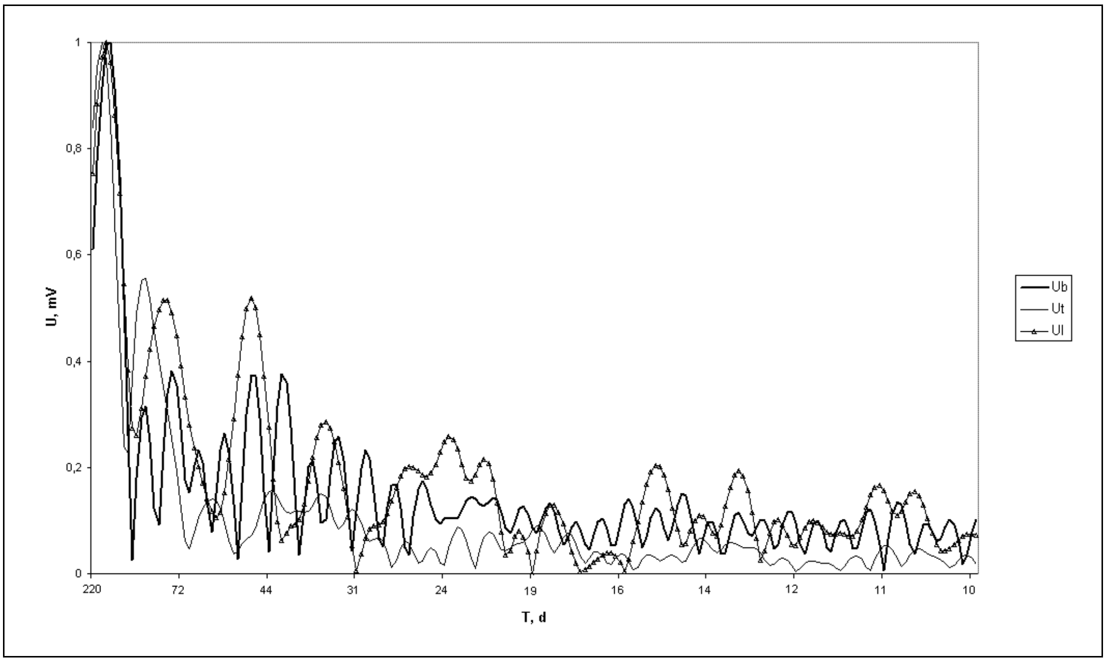

Fig. 2: Normalized amplitude spectra of the signals of bottom detector U_b, top one U_t and lab one U_l.

For causal analysis we used low-pass filtered data (at periods T>77d). Hereafter the relative error of γ and $i_{X|Y}$ estimations is less than 10%. In Fig.3 the results for the bottom and top detectors are presented. γ>1 that is U_t is the cause and U_b is the effect. At τ>0 we observe classically forbidden time reversal causality. It is just weak causality allowed only for the entangled states. Moreover, there are three causality maxima: advanced, approximately synchronous and symmetric retarded. Each maximum of causality γ corresponds to minimum of independence $i_{X|Y}$. The highest maximum of γ=1.8 and the deepest minimum of $i_{X|Y}$=0.25 are at advancement 22 d. Corresponding advanced correlation r=0.87±0.00.

The similar picture with three γ maxima was observed in our previous experiments in case of relatively close source-processes [18, 19, 21]. It is in agreement with Eq. (1) predicting detector responses with two symmetric time shifts, while the synchronous response can be a result of advanced/retarded signal interference. And in those experiments in case of distant source-processes prevailing the retarded (and hence synchronous) response was suppressed owing to absorption and only significant advanced one remained [18, 23, 29].

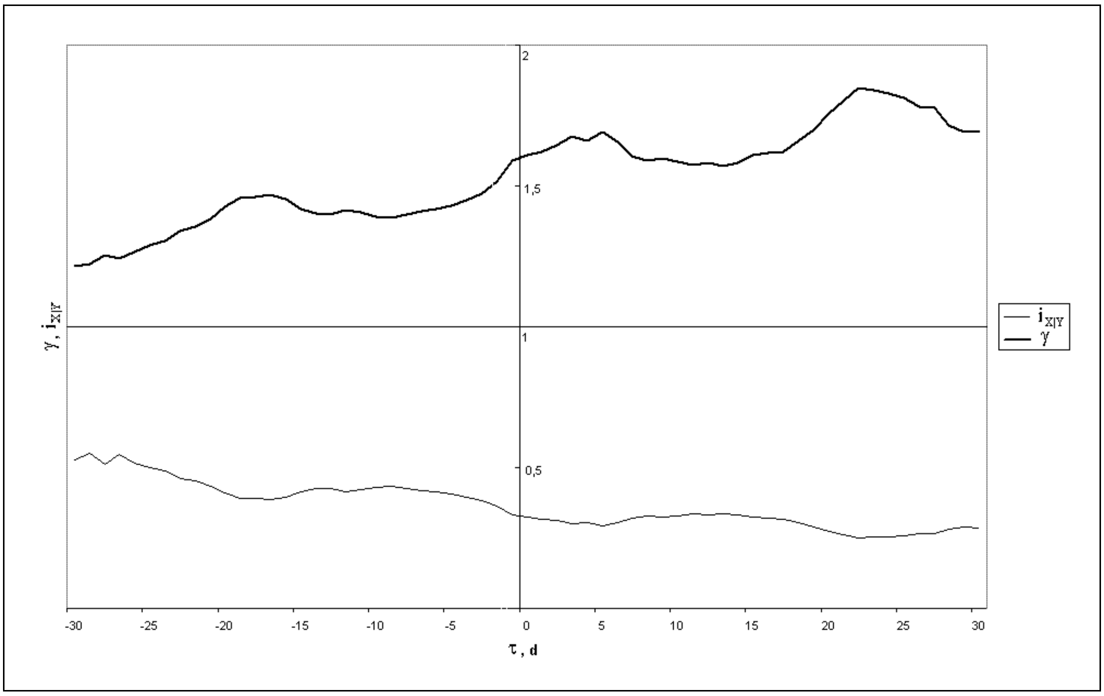

Fig. 3: Causal analysis of U_b (X) and U_t (Y). τ<0 corresponds to retardation of U_b relative U_t, τ >0 – to advancement.

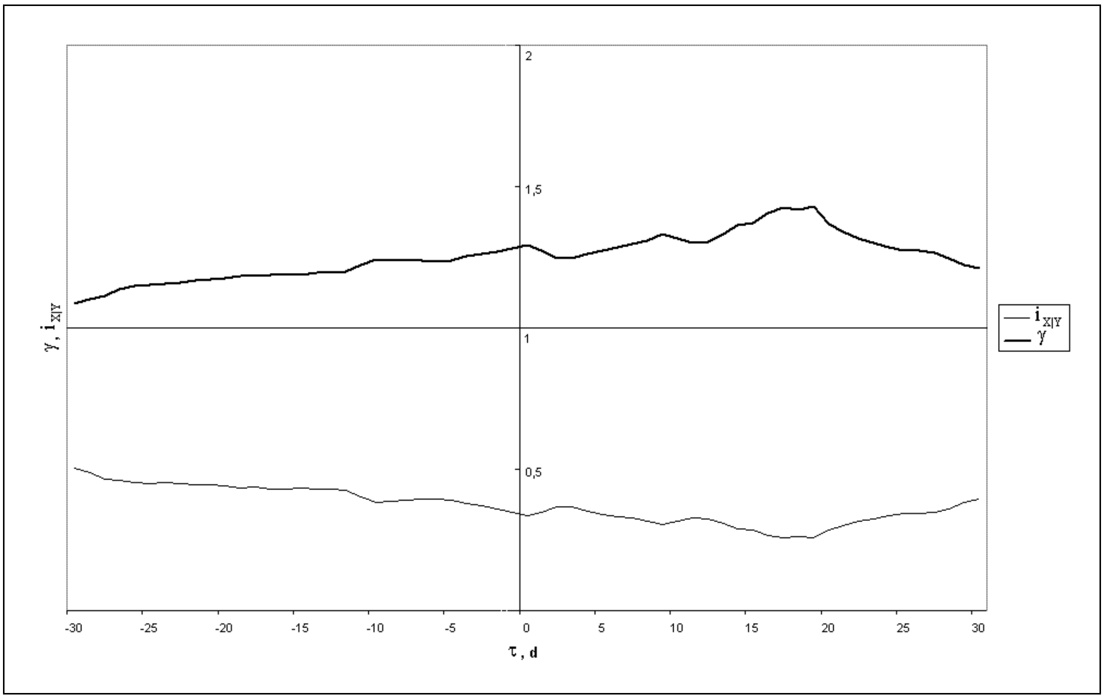

Fig. 4: Causal analysis of U_t (X) and U_l (Y). τ<0 corresponds to retardation of U_t relative U_l, τ>0 – to advancement.

In Fig. 4 causal analysis of the top detector U_t and the distant one U_l is presented. γ>1 that is U_l is a cause with respect to U_t, and again this causal connection is time reversal. We observe the single $\max \gamma = 1.4$ at advancement 20 *d*. Corresponding $\min i_{X|Y} = 0.20$ and (not shown in this figure) $\max r = 0.97 \pm 0.00$.

And in Fig.5 causal analysis of the bottom detector U_b and distant one U_l is presented. Again U_l is a cause with respect to U_b and causality is time reversal. $\max \gamma = 1.7$ at advancement 25 *d*. Corresponding $\min i_{X|Y} = 0.28$ and $\max r = 0.66 \pm 0.01$.

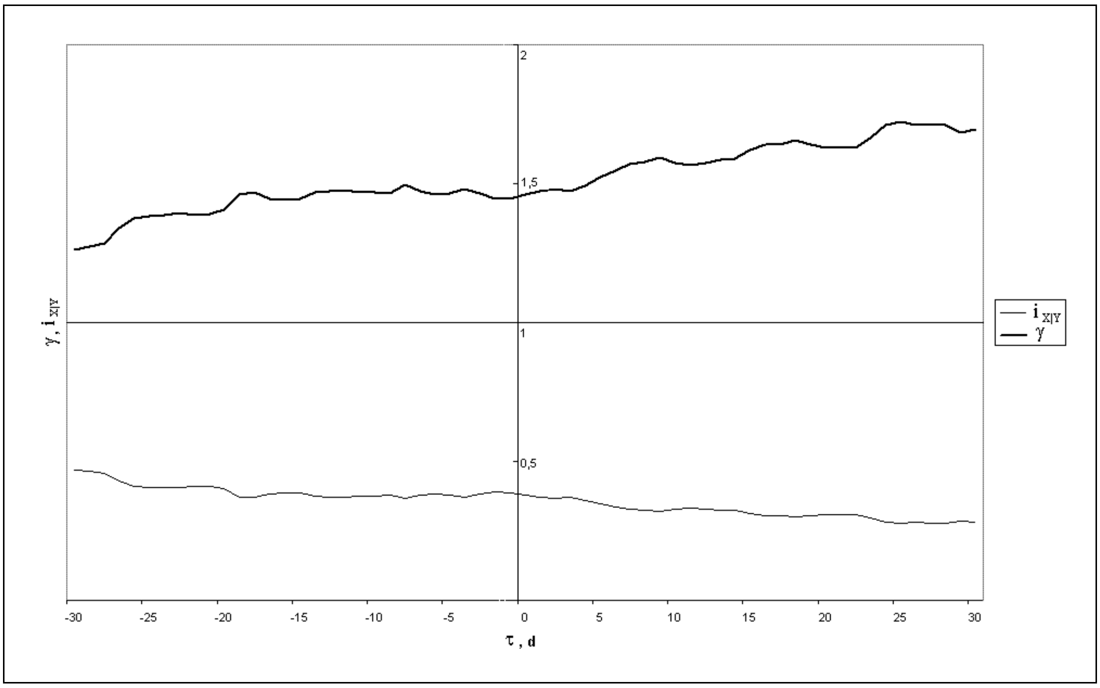

Fig. 5: Causal analysis of U_b (X) and U_l (Y). τ<0 corresponds to retardation of U_b relative U_l, τ >0 – to advancement.

Thus we may conclude that by data of three detectors the causal connection is directed downwards, from the Earth surface to the lake floor. It is quite natural for the external heliogeophysical source-processes, but this causality is time reversal: the effects appear before the causes!

Consideration of correlation between the detector signals and such global processes will be the subject of our subsequent work, by now we can present a result concerning one possible regional source-process, which is variation of the subsurface temperature measured by our setup at the depth 22 *m*. This variation absolutely can not classically influence on the bottom detector and only slightly can on the top one.

In Fig. 6 the amplitude spectra (in absolute units) of both the detectors and temperature *t* are presented. It is seen that the main maxima of the detector signals do not correspond to the temperature one. There are some small corresponding maxima of *t* and U_t (e.g. at T=34.4 *d*). But even this correspondence can not be explained by the classical influence. The fact is, the temperature coefficient of these electrodes equals 0.04 *mV/K*. As the temperature amplitude strongly decays with the depth (the U_t detector is set 30 *m* deeper than the *t* sensor) the spectral amplitude ratio must be less than this value. But it proves to be much greater (>1 *mV/K*). It could be explained only by some nonlocal correlation.

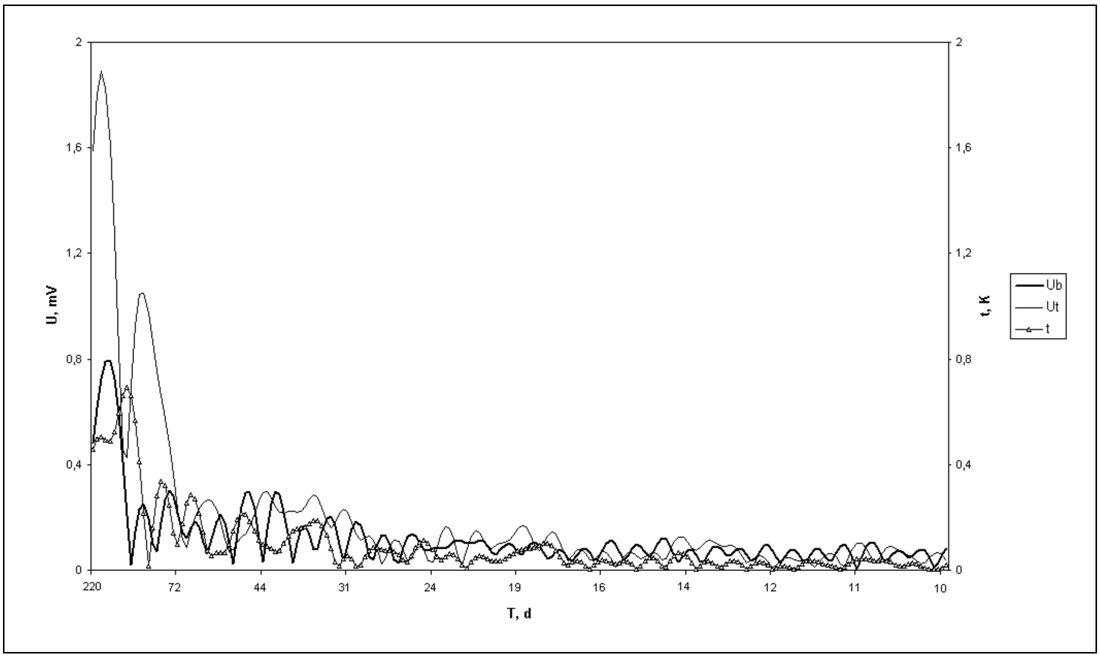

Fig. 6: Amplitude spectra of the bottom detector U_b, top one U_t and temperature t at the depth 22 *m*.

Consider the results of causal and correlation analysis of U_t and t (Fig. 7) with the same low-pass filtration. We observe that t is a cause with respect to U_t with two equal (1.6) γ maxima at almost symmetric retardation (-40 *d*) and advancement (45 *d*). But the advanced $\min i_{X|Y} = 0.17$ is deeper than the retarded ones (1.3 times). And the advanced correlation $\max r = 0.99 \pm 0.00$ is also much greater than the retarded extremum (1.6 times). It is just manifestation of advanced macroscopic nonlocal correlation.

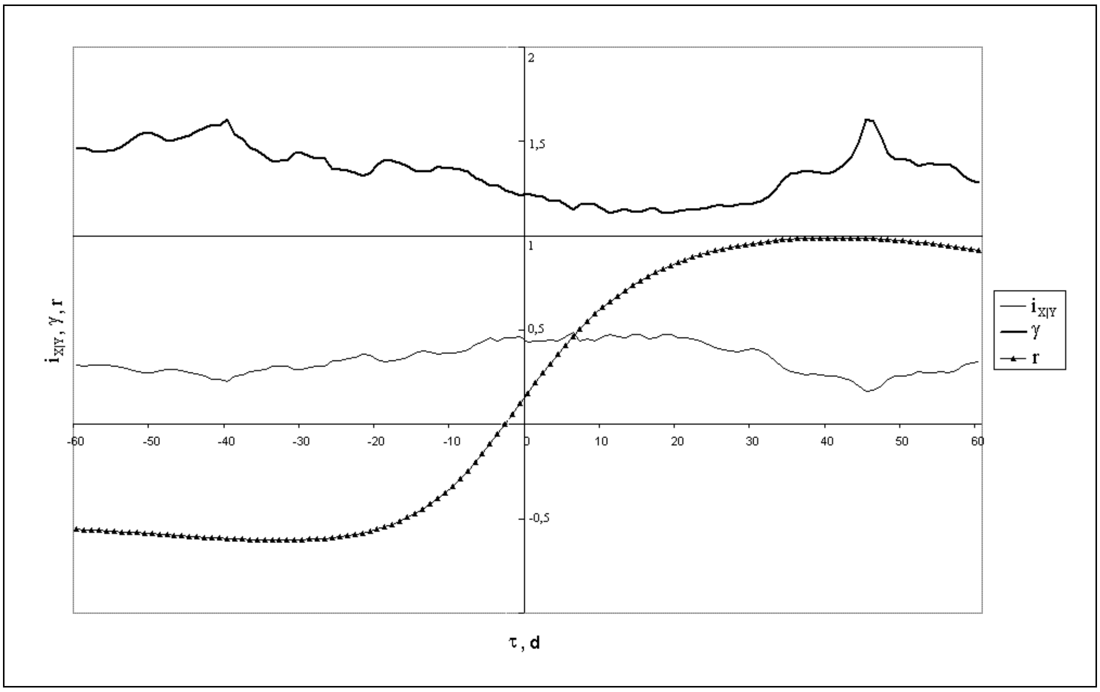

Fig. 7: Causal and correlation analysis of U_t (X) and t (Y). τ<0 corresponds to retardation of U_t relative t, τ>0 – to advancement.

We have applied to these data the forecasting algorithm based on computation of current (sliding) regression. This algorithm needs rather long training interval; hence we could test the forecast only by relatively short segment of the time series. The result is presented in Fig. 8. The forecasting curve showed in this figure is obtained by means of day by day forecasting with fixed advancement τ=45 *d*. The accuracy of the forecast is acceptable for all practical purposes.

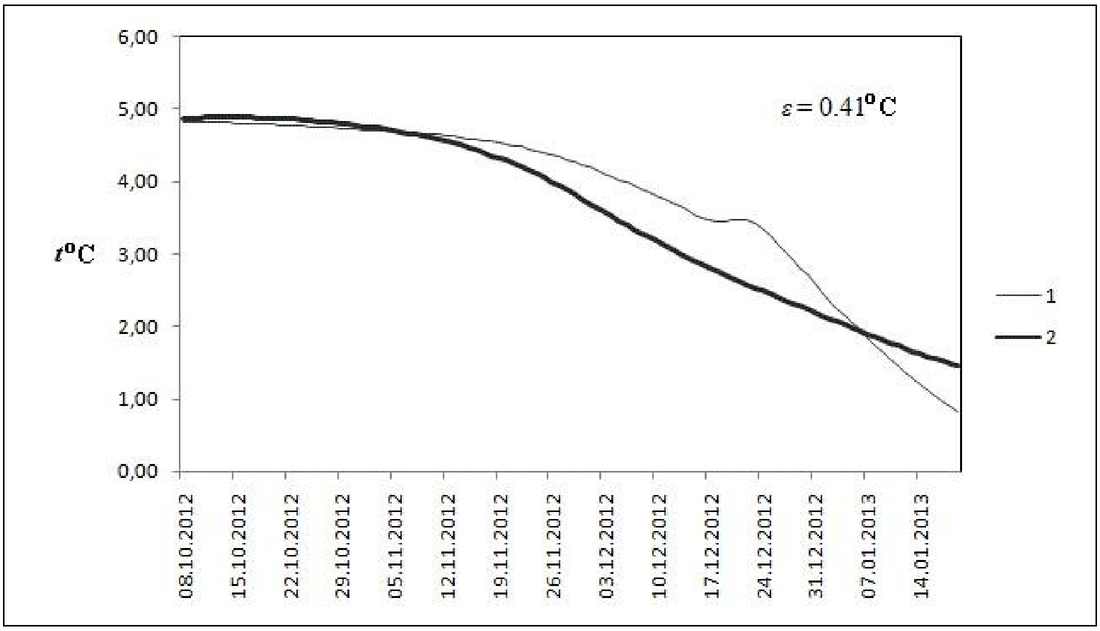

Fig. 8: The forecast of subsurface temperature with advancement 45 days (1) as compared to the factual one (2). The ε is the standard deviation of the forecasting and factual curves.

Conclusion

The long-term Baikal Deep Water Experiment, on study of macroscopic entanglement and related phenomena of advanced nonlocal correlations in reverse time, has begun. The experiment includes measurements with three nonlocal correlation detectors at the depths 52 and 1216 *m* in the Baikal Lake, and at spaced at 4200 *km* laboratory in Troitsk. Detector signals have to be correlated to each other and with large-scale random geophysical and astrophysical source-processes.

The first result is reliable establishment of detector signal time reversal causal connection. It is the most prominent property of macroscopic entanglement and manifestation of quantum principle of weak causality.

In addition, study of subsurface temperature variation in the Baikal, as a regional source-process, has revealed advanced detector signal response, which has been used for the temperature forecast.

Acknowledgements

The authors thank G.V. Domogatsky and A.I. Panfilov fo their contribution to the experiment. This work was supported by RFBR (grants 12-05-00001 and 12-05-98009).

References

[1] Cramer, J.G. (1980). “Generalized absorber theory and Einstein-Podolsky-Rosen paradox”.

Phys. Rev D 22: 362-376.
[2] Laforest, M., Baugh, J and Laflamme, R. (2006). “Time-reversal formalism applied to bipartite entanglement: theoretical and experimental exploration”. Phys. Rev. A 73: 032323.
[3] Lloyd, S., Maccone L., Garcia-Patron, R., Giovannetti, V., Shikano, Y., Pirandola, S., Rozema, L.A., Darabi, A., Soudagar, Y, Shalm, L.K. and Steinberg, A.M. (2011). “Closed timelike corves via post-selection: theory and experimental demonstration”. Phys. Rev. Lett. 106: 040403.
[4] Ma, X.-S., Zotter, S., Kofler, J., Ursin, R., Jennewien, T., Brukner, Č. and Zeilinger, A. (2012). “Experimental delayed-choice entanglement swapping”. Nature Physics 8: 479-485.
[5] Megidish, E., Halevy, A., Shacham, T., Dvir, T., Dovrat, L. and Eisenberg, H.S. (2013). “Entanglement Between Photons that have Never Coexist”. Phys. Rev. Lett. 110: 210403
[6] Plenio, M.B., Huelga, S.F., Beige, A. and Knight, P.L. (1999). “Entangling two qubits by dissipation”. Phys. Rev. A: 59: 2468–2475
[7] Basharov, A.M. (2002). “Decoherence and Entanglement by Radiation Decay of Two-Atom System”. J. Exp. Theor. Phys. 121: 1249-1260.
[8] Plenio, M.B. and Huelga, S.F. (2002). “Entangled light from white noise”. Phys. Rev. Lett. 88: 197901.
[9] Kim, M.S., Lee, J., Ahn, D. and Knight, P.L. (2002). “Entanglement induced by a single-mode heat environment”. Phys. Rev. A 65: 040101.
[10] Braun, D., (2002). “Creation of Entanglement by Interaction with a Common Heat Bath”. Phys. Rev. Lett. 89: 277901.
[11] Jakobczyk, L. (2002). “Entangling two qubits by dissipation”. J. Phys. A 35: 6383-6392.
[12] Benatti, F., Floreanini, R. and Piani, M. (2003). “Environment induced entanglement in Markovian dissipative dynamics”. Phys. Rev. Lett. 91: 070402.
[13] Choi, T., and Lee, H.J. (2007). “Quantum entanglement induced by dissipation”. Phys. Rev. A: 76: 012308.
[14] Kozyrev, N.A., and Nasonov, V.V. (1978). In: Astrometry and Heavenly Mechanics, edited by A.A. Efimov, (VAGO Press, Moscow), pp. 168-179 (in Russian).
[15] Kozyrev, N.A., and Nasonov, V V. (1980). In Manifestation of Cosmic Factors on the Earth and Stars, edited by A.A. Efimov, (VAGO Press, Moscow), pp. 76-84 (in Russian).
[16] Cramer, J.G. (1986). “The transactional interpretation of quantum mechanics”. Rev. Mod. Phys. 58: 647-688.
[17] Korotaev, S.M., Morozov, A.N., Serdyuk, V.O., Gorohov, J.V. and Machinin, V.A. (2005). “Experimental study of macroscopic nonlocality of large-scale geomagnetic dissipative processes”. NeuroQuantology 3: 275-294.
[18] Korotaev, S.M. (2011) “Causality and Reversibility in Irreversible Time” (Scientific Research Publishing, Inc., USA).
[19] Korotaev, S.M., Serdyuk, V.O., Sorokin, M.O. and Abramov, J.M. (1999). “Geophysical manifestation of interaction of the processes through the active properties of time”. Phys. Chem. Earth (A) 24: 735-740.
[20] Korotaev, S.M., Serdyuk, V.O. and Sorokin, M.O. (2000). “Effect of macroscopic nonlocality on geomagnetic and solar-ionospheric Processes”. Geomagnetism and Aeronomy 40: 323-330.
[21] Korotaev, S.M., Morozov, A.N., Serdyuk, V.O. and Sorokin, M.O. (2002).

"Manifestation of macroscopic nonlocality in some natural dissipative processes". Russian Phys. J. 45 (5): 3-14.
[22] Korotaev, S.M. (2006). "Experimental study of advanced correlation of some geophysical and astrophysical processes". Int. J. of Computing Anticipatory Systems 17: 61-76.
[23] Korotaev, S.M., and Serdyuk, V.O. (2008). "The forecast of fluctuating large-scale natural processes and macroscopic correlations effect". Int. J. of Computing Anticipatory Systems 20: 31-46.
[24] Hoyle, F. and Narlikar, J.V. (1995). "Cosmology and Action-at-a-Distance Electrodynamics". Rev. Mod. Phys. 67: 113-156.
[25] Korotaev, S.M., Serdyuk, V.O., Nalivaiko, V.I., Novysh, A.V., Gaidash, S.P., Gorokhov, Yu.V., Pulinets, S.A. and Kanonidi, Kh.D. (2003). "Experimental estimation of macroscopic nonlocality effect in solar and geomagnetic activity". Phys. of Wave Phenomena: 11: 46-55.
[26] Korotaev, S.M., Serdyuk, V.O., Gorohov, J.V. Pulinets, S.A. and Machinin, V.A. (2004). "Forecasting effect of macroscopic nonlocality". Frontier Perspectives 13 (1): 41-45.
[27] Korotaev, S.M., Morozov, A.N., Serdyuk, V.O., Gorohov, J.V., Machinin, V.A. and Filippov, B.P. (2007). "Experimental study of advanced nonlocal correlations of the process of solar activity". Russian Phys. J. 50: 333-341.
[28] Korotaev, S.M., Serdyuk, V.O. and Gorohov, J.V. (2007). "Forecast of geomagnetic and solar activity on the nonlocal correlations". Doklady Earth Sciences 415A: 975-978.
[29] Korotaev, S.M., Serdyuk, V.O. and Gorohov, J.V. (2007). "Forecast of solar and geomagnetic activity on the macroscopic nonlocality effect". Hadronic Journal 30: 39-56.
[30] Korotaev, S.M., and Kiktenko, E.O. (2010). "Causal analysis of the quantum states". Search for Fundamental Theory. AIP Proceedings 1316: 295-331.
[31] Kiktenko, E.O. and Korotaev, S.M. (2012). "Causal analysis of asymmetric entangled states". Physics Letters A 376: 820-823.
[32] Korotaev, S.M. and Kiktenko, E.O. (2012). "Causality and decoherence in the asymmetric states" Physica Scripta 85: 055006.
[33] Korotaev, S.M. (1992). "On the possibility of causal analysis of the geophysical processes". Geomagnetism and Aeronomy 32 (1): 27-33.
[34] Korotaev, S.M., Shabelyansky, S.V. and Serdyuk, V.O. (1992). "Generalized causal analysis and its employment for study of electromagnetic field in the ocean". Izvestia Phys. of the Solid Earth 6: 77-86.
[35] Hachay, O.A., Korotaev, S.M. and Troyanov, A.K. (1992). "Results of application of the causal analysis to seismoacoustic and electromagnetic emission borehole data processing". Volcalonogy and Seismology 3: 92-100.
[36] Korotaev, S.M., Hachay, O.A. and Shabelyansky, S.V. (1993). "Causal analysis of the process of horizontal informational diffusion of electromagnetic field in the ocean". Geomagnetism and Aeronomy 33(2): 128-133.
[37] Korotaev, S.M. (1995). "Role of different definitions of the entropy in the causal analysis". Geomagnetism and Aeronomy 35 (3): 387-393.
[38] Lean, J.L. and Brueckner, G.E. (1989). "Intermediate-term solar periodicities: 100-500 days". Astrophys. J. 337: 568-578.