# 7 Other research

## 7.1 Status of nonlocal quantum communication test

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The question we have been investigating in this experiment is whether the intrinsic nonlocality of standard quantum mechanics is the private domain of Nature, as is generally assumed by the physics community, or whether in special circumstances the nonlocal connection between subsystems can be used to send signals from one observer to another. The basic scheme, as described in the references, is to use the which-way information implicit in momentum-entangled photon pairs to create a signal as the presence or absence of an interference pattern at the receiving end, depending on whether or not which-way information was extracted at the sending end of the experiment.

With the aid of generous private contributions and some use of CENPA resources, we have continued work on this test of nonlocal quantum communication, which has been reported in the past six years[1,2,3,4,5,6]. The Mark I configuration of the experiment, as described in the first two references, employed a high-power argon-ion laser operating at about 1 W in the ultraviolet at 351 nm, which pumped nonlinear crystals (BBO or $LiIO_3$) to produce pairs of momentum-entangled 702-nm photons, on which measurements were subsequently performed, mainly by attempting to detect an interference pattern with a cooled quantum-sensitive camera and later with avalanche photodiodes operated in the linear mode. It was concluded that the detectors used were too insensitive and that signal-to-noise limitations from fluorescence photons competing with the downconverted photons in the crystals prevented the planned measurements with the initial Mark I configuration.

The work was moved to the Optics Laboratory on the 2nd floor of the Physics-Astronomy Building, which offered the advantage that the experimental area could be darkened without interference with other experiments. A new Mark II experimental configuration, described in the 2011 CENPA Annual Report[5], used a periodically-poled potassium titanyl phosphate (ppKTP) crystal with a 10-$\mu$m poling length and dimensions 1 mm$\times$2 mm$\times$30 mm made by Raicol, Inc. The ppKTP crystal was maintained at 50° C in a precision crystal oven and optically pumped with a 405-nm Sacher Littow-type grating-stabilized diode laser. A system of avalanche photodiodes (APDs) operated in the Geiger mode was used to detect the single 810-nm photons. Problems with detector noise (spontaneous avalanches $\sim$ 10,000 counts/second) were encountered. We tried re-purposing an X-ray detector cryostat to cool an array of APDs with light fibers attached to temperatures as low as 77 K with liquid nitrogen, but we found

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[1]CENPA Annual Report, University of Washington (2007) p. 52.
[2]CENPA Annual Report, University of Washington (2008) p. 42.
[3]CENPA Annual Report, University of Washington (2009) p. 41.
[4]CENPA Annual Report, University of Washington (2010) p. 93.
[5]CENPA Annual Report, University of Washington (2011) p. 94.
[6]CENPA Annual Report, University of Washington (2012) p. 89.

that the avalanche threshold voltage and detector noise level diminished together with temperature, so that the spontaneous avalanche counting rate remained relatively constant with temperature. We also investigated whether the noise problem could be reduced or eliminated by pulsing the pump laser. At best, pulsing gained perhaps a factor of 10 improvement in signal-to-noise, but this was insufficient to deal with the noise problem.

In early 2012 the Sacher grating-stabilized diode laser failed, partly as a result of operation in the pulsed mode. Repair by Sacher proved to be prohibitively expensive. It was replaced by a high-power Opnext HL40023MG blue-violet laser diode nominally rated for 400 mW at wavelength 405 nm. The Opnext laser unit was extensively tested using the Optics Laboratory's high-precision grating spectrograph. It was determined that the Opnext unit could produce in excess of 700 mW with good line shape at central wavelengths ranging from 402 nm to 408 nm, depending on the operating temperature of the diode. We found that operating the Opnext unit at around 60° C produced a good laser line at 405 nm as needed for the experiment. The implication of this work was that a superior source of entangled 810-nm photon pairs could be produced by pumping the ppKTP crystal with a temperature-stabilized Opnext HL40023MG laser diode. We did not, however, proceed to develop the needed temperature control at that time. Unfortunately, despite further work in 2012, no way was found to reduce the noise in the APDs to an acceptable level.

The Mark II version of the experiment has now been concluded without results. The two preliminary versions of the experiment have highlighted important problems, pointing to an improved Mark III experimental design now in development. We have learned the following lessons: (1) Avalanche photodiodes, even when cooled to as low as 77 K with liquid nitrogen, are simply too noisy to meet the single-photon detection requirements of the experiment and cannot be used for the needed non-coincident single photon counting; (2) the choice of a grating-stabilized laser in the Mark II design resulted in pump power levels that were too low for efficient production of entangled photon pairs and ultimately led to declining output and laser failure (the choice of a "bare" temperature stabilized single-mode laser diode would have been better); (3) the Mach-Zehnder interferometers used in the preliminary experiments are very difficult to align and maintain, and they accept too many optical modes, so that the interference patterns produced, instead of being an "on" bright spot or an "off" dark spot, is a "bulls-eye" interference patterns with a bright or dark center (single mode interferometer operation would have been better); and (4) at a pump wavelength of 405 nm and entangled photon pairs at 810 nm, the use of fiber optics and commercially available fiber-based devices is limited in the present experimental design because the operating wavelength is too far from the communications-industry-standard wavelengths of 1064, 1310 (O-Band), and 1550 nm (C-Band). Longer wavelength pump lasers and modified poling of the ppKTP crystal are needed.

With these lessons in mind, we are working on a Mark III version of the experiment that would use (1) cryogenic noise-free superconducting-transition detectors[1] to efficiently detect the photons of interest, (2) an entangled photon-pair source using a 1-W, 532-nm green diode pump laser to produce photon pairs at 1064 nm from a ppKTP nonlinear crystal with

[1] Daiji Fukuda *et al.*, Opt. Express **19** 870 (2011).

350-$\mu$m poling length, and (3) a fiber-based set of switched Mach-Zehnder interferometer units optimized for 1064 nm to replace the system of lenses, prisms, and mirrors used in the previous versions. We have been encouraged to prepare a pre-proposal aimed at seeking funding from a government agency to support construction and operation of the new Mark III version of the experiment.

## 7.2 Energy deposition and micro dosimetry in water for fast ions in radiation therapy

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Studies of the interactions of fast heavy ions with water made in relation to cancer therapy have been published[1,2] in past annual reports. A detailed report was written and published[3] in the last year.

A description of the subject was presented at the CENPA Monday meeting on 9 January, 2012.

A study of similar methods for relativistic particles was also published[4] recently.

Both of these studies may be of interest in connection with the installation of two proton cyclotrons for radiation therapy in Seattle.

[1] CENPA Annual Report, University of Washington (2010) p. 98.

[2] CENPA Annual Report, University of Washington (2011) p. 91.

[3] "Stochastics of Energy Loss and Biological Effects of Heavy Ions in Radiation Therapy," Hans Bichsel, chapter 1 in *Theory of Heavy Ion Collision Physics in Hadron Therapy*, Advances in Quantum Chemistry, D. Belkic, ed., vol. 65, J. R. Sabin and E. Braendas, series eds., Elsevier (2013) and AP, ISBN: 978-0-12-396455-7, ISSN:0065-3276.

[4] "The interaction of radiation with matter," Hans Bichsel, chapter 2 in Landolt-Boernstein, vol. 21 *Elementary Particles, Nuclei and Atoms*, subvol. B, "Detectors for Particles and Radiation," C. W. Fabian and H. Schopper, eds., Springer (2011), ISBN: 978-3-642-03605-7, ISSN:1615-1844.