Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres

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For more than 80 years, the counterintuitive predictions of quantum theory have stimulated debate about the nature of reality [1]. In his seminal work [2], John Bell proved that no theory of nature that obeys locality and realism can reproduce all the predictions of quantum theory. In any local realist theory the correlations between distant measurements satisfy an inequality that can be violated according to quantum theory if the measurements are performed on entangled particles. In the past decades, numerous ingenious Bell inequality tests have been reported [3]. However, because of experimental limitations, all experiments to date required additional assumptions to obtain a contradiction with local realism, resulting in loopholes [3].

Here I will present a Bell experiment that is free of any such additional assumption and thus directly tests the principles underlying Bell's inequality [4]. We employ an event-ready scheme that enables the generation of robust entanglement between distant electron spins (estimated state fidelity of 0.92 ± 0.03). Efficient spin readout avoids the fair sampling assumption (detection loophole), while the use of fast random basis selection and spin readout combined with a spatial separation of 1.3 km ensure the required locality conditions. We perform 245 trials testing the CHSH-Bell inequality $S \leq 2$ and find $S = 2.42 \pm 0.20$. A null hypothesis test yields a probability of at most p = 0.039 that a local-realist model for space-like separated sites could produce data with a violation at least as large as we observe, even when allowing for memory in the devices ; a large class of local realist theories is thus rejected. This result paves the way for further bounding of the statistical uncertainty, for testing less conventional theories, and for implementing device-independent quantum-secure communication [5] and randomness certification [6].

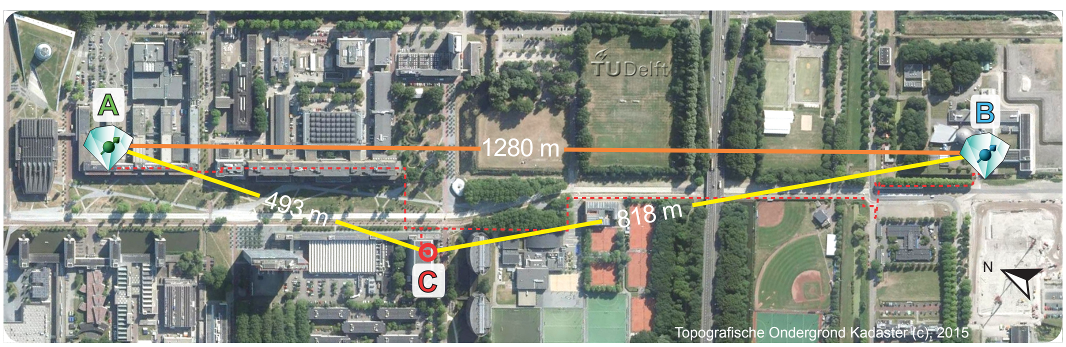

FIGURE 1. Aerial photograph of the campus of Delft University of Technology where entanglement was generated between two electron spins in diamond located at positions A and B. The location C serves as an intermediate station necessary for the remote entanglement protocol. The red dotted line marks the path of the optical fiber connecting the three setups.

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