Spooky Work at a Distance: An Interaction-Free Quantum Measurement Driven Engine

Cyril Elouard
Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627, USA
cyril.elouard@gmail.com

Mordecai Waegell
Institute for Quantum studies, Chapman University, Orange, CA 92866, USA

Benjamin Huard
Laboratoire de Physique, École Normale Supérieure de Lyon, 46 allée dItalie, 69364 Lyon Cedex 7, France

Andrew N. Jordan
Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627, USA

Abstract: We propose an engine fueled by an interaction-free measurement, able to lift a quantum particle in the gravitational potential. The energy is provided by the probe, a single photon, in a seemingly nonlocal way.
OCIS codes: 270.5580, 000.6800, 260.2160

Recently, a lot of attention has been paid to the energy associated with the wavefunction collapse process. The fact that energy may be stochastically transferred from the measurement probe to the system being measured allowed to design highly efficient quantum measurement-powered engine [1–4]. In particular, in Ref. [3], a massive quantum particle is lifted in a linear potential owing to generalized position measurement followed by feedback. Here we show that such work extraction can be done in a seemingly nonlocal way using interaction-free measurements, despite a spatially local coupling between the probe and the measured system.

Our setup is a modification of the famous Elitzur-Vaidman bomb tester [5], a paradigmatic example of interaction-free measurement: a very sensitive bomb, which goes off when absorbing a single photon, is placed in one arm of a tuned Mach-Zehnder interferometer. The detection of a photon in the so-called dark port of the interferometer indicates the bomb's presence. As the photon was transmitted until the detector, it was not absorbed by the bomb which therefore did not explode. In the end, the presence of the bomb was ascertained without blowing it up (see Fig. 1a).

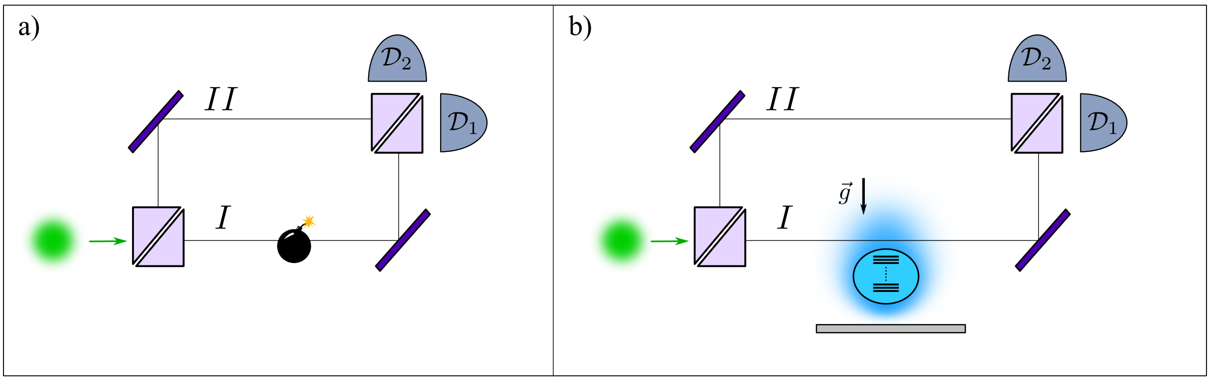

Fig. 1. a) The Elitzur-Vaidman bomb tester [5]. The interferometer is tuned such that if both arms are empty, the photon always exits by the port of detector $\mathscr{D}_1$. A click at detector $\mathscr{D}_2$ ascertains the presence of the bomb in arm II. b) Our proposal. The bomb is a quantum mechanical massive particle above a rigid platform and subject to a gravitational force. Its ground state wavefunction has spatial spread overlapping partially with arm I. In addition, the bomb has a continuum of internal degrees of freedom able to absorb the photon.

In our proposal (see Fig. 1b), we treat the bomb quantum mechanically, and consider that its ground state wavefunction exists in a superposition of being localized inside and outside the interferometer arm. This situation is realized e.g. if the bomb is a massive particle above a rigid platform, subject to a gravitational force. As in the Elitzur-Vaidman setup, a click at the dark port of the interferometer reveals the presence of the bomb inside the arm, and as a consequence the bomb's wavefunction collapses to a completely state localized inside the arm. This process increases the bomb's energy as the post-measurement state differs from the initial ground state. In particular, the average altitude of the bomb has increased, corresponding to non-zero potential energy. This potential energy can then be extracted in an engine cycle, e.g. by raising the rigid platform like in Ref. [3].

Crucially, the wavefunction collapse of the bomb inside the interferometer arm indicates the photon could not have taken the path the bomb was localized in, otherwise the latter would have absorbed the photon and exploded. Therefore, the work done on the bomb by the photon is seemingly nonlocal. We show that this effect happens even though the bomb and the photon are coupled via a spatially local interaction Hamiltonian. To do this, we model the bomb by its motional degree of freedom, a massive particle in the potential composed of the platform and the linear potential, and its internal Hamiltonian that is treated as a zero temperature reservoir able to absorb the photon with a rate Γ of both the bomb and the photon are present in the same arm of the interferometer. An almost perfect absorption is guaranteed if either the product $\Gamma\tau$ where τ is the photon-bomb interaction time in arm I is large enough. Each arm of the interferometer is assumed to contain one photon mode, characterized by a mean frequency ω_{ph} and a linewidth $\Delta\omega_{\mathrm{ph}}$.

Our model allows to check explicitly that the energy needed to collapse the bomb inside the arm is provided by the photon, whose average frequency gets red-shifted of the corresponding amount of energy E_{m}, set by the Hamiltonian of the motional degree of freedom of the bomb. Interestingly, the need to preserve the interference at the exit beam-splitter requires that this shift is small with respect to the initial energy uncertainty of the photon. There is therefore a fundamental bound on the amount of energy that can be exchanged in a interaction-free manner, which is:

$$E_{\mathrm{m}} \ll \hbar\Delta\omega_{\mathrm{ph}}. \tag{1}$$

In order to gain further insights about the phenomenon, we compute the weak value of various observables involved in the problem, at time t. Such quantity corresponds to the expectation value of the corresponding observable in presence of postselection at the final time t_{f} [6]. In our case, we postselect on the dark port firing, i.e. the bomb not exploding and being successfully lifted. We identify anomalous weak values, i.e. lying outside the range of the observable's eigenvalues. Such phenomenon is known to be occur in presence of contextuality [7], and is equivalent to the violation of a generalized Leggett-Garg inequality [8,9]. The contextuality of the problem becomes apparent when noting that different sets of weak values suggest a different interpretations of how the energy exchange occurs. The weak values of projectors onto the regions inside and outside the arm support the nonlocal energy exchange interpretation: e.g., the projector onto the photon going through the arm of the bomb and onto the bomb being inside the arm is zero. On the other hand, the weak-values involving the energy eigenstates of the bomb suggest a surprising story: non-zero photon weak values in the arm of the bomb show that a pair of effective particles, one of them with negative energy, is created in the arm of the bomb and exchange energy with it before recombining with the photon at the exit beam splitter.

We have proposed an engine fueled by an interaction-free measurement, and showed that the energy source is a single photon which seemingly does not interact with the battery, the motional degree of freedom of the bomb. Regardless of interpretation, this interaction free quantum measurement engine is able to lift the most sensitive bomb without setting it off. More details about the derivation and the results can be found in Ref. [10].

References

1. Elouard, C., Herrera-Mart, D., Huard, B., Auffves, A., "Extracting Work from Quantum Measurement in Maxwells Demon Engines", Phys. Rev. Lett., **118**, 260603 (2017). doi:10.1103/PhysRevLett.118.260603
2. Yi, J., Talkner, P., Kim, Y. W, "Single-temperature quantum engine without feedback control", Phys. Rev. E, **96**, 022108 (2017). doi:10.1103/PhysRevE.96.022108
3. Elouard, C., Jordan, A. N., "Efficient Quantum Measurement Engines." Phys. Rev. Lett. **120**, 260601 (2018). doi:10.1103/PhysRevLett.120.260601
4. Ding, X., Yi, J., Kim, Y. W., Talkner, P., "Measurement-driven single temperature engine" Phys. Rev. E **98**, 042122 (2018). doi:10.1103/PhysRevE.98.042122
5. Elitzur, A. C., Vaidman, L., "Quantum mechanical interaction-free measurements" Found. Phys., **23**, 987997 (1993). doi:10.1007/BF00736012
6. Aharonov, Y., Albert, D. Z. and Vaidman, L, "How the result of a measurement of a component of the spin of a spin-1/2 particle can turn out to be 100", Phys. Rev. Lett. **60**, 1351–1354 (1988),10.1103/PhysRevLett.60.1351.

7. Pusey, M. F., “Anomalous Weak Values Are Proofs of Contextuality”, Phys. Rev. Lett. **113**, 200401 (2014), 10.1103/PhysRevLett.113.200401.
8. Leggett, A. J. and Garg, A., “Quantum mechanics versus macroscopic realism: Is the flux there when nobody looks?”, Phys. Rev. Lett. **54**, 857–860 (1985), doi:10.1103/PhysRevLett.54.857.
9. Williams, N. S. and Jordan, A. N., “Weak Values and the Leggett-Garg Inequality in Solid-State Qubits”, Phys. Rev. Lett. **100**, 026804 (2008), doi:10.1103/PhysRevLett.100.026804.
10. Elouard, C. and Waegell, M. and Huard, B. and Jordan, A. N., “Spooky Work at a Distance: an Interaction-Free Quantum Measurement-Driven Engine”, arXiv preprint, arXiv:1904.09289 (2019) https://arxiv.org/abs/1904.09289