an *ad hoc* restriction on observables. Thus, one may ask: ‘Does also relaxing the IP allow an even richer classification of statistics by the transformation properties of states *and observables* under the action of particle permutations?’

And indeed it does, as Espinoza et al. [8] have recently shown. Bose and Fermi particles – what are usually called ‘quanta’ – are of course still examples of the types now classified, as are parastatistical particles and quantum Maxwell–Boltzmann particles, and a countable infinity of others. In every case categorized by Hartle, Stolt and Taylor (except for bosons and fermions which necessarily satisfy the indistinguishability postulate) there is an associated distinguishable case now possible in which non-symmetric observables are allowed. Any two systems with different statistics – whether they differ in the transformation properties of their states or observables or both – will have different partition functions and hence different thermodynamic behaviors. In particular, whether the indistinguishability postulate holds makes a real physical difference for a system of identical particles – or at least it would were we to discover identical yet distinguishable particles in nature.



## Literature


1. E. Castellani (ed.): *Interpreting Bodies: Classical and Quantum Objects in Modern Physics* (Princeton University Press, Princeton, NJ 1998).
2. J.M. Jauch: *Foundations of Quantum Mechanics* (Addison-Wesley, New York 1968).
3. O.W. Greenberg: Particles with Small Violations of Fermi or Bose Statistics. Phys. Rev. D 43, 4111-20 (1991).
4. Bros, A.M.L. Messiah and D.N. Williams: Theoretical Basis of the Symmetrization Postulate. Phys. Rev. 149, 1008–9 (1966).
5. S. Saunders: On the Explanation for Quantum Statistics. Stud. Hist. Philos. Mod. Phys. 37, 192-211 (2006).
6. A.M.L. Messiah and O.W. Greenberg: Symmetrization Postulate and Its Experimental Foundation. Phys. Rev. 136, B248-67 (1964).
7. J.B. Hartle, R.H. Stolt and J.R. Taylor: Paraparticles of Infinite Order. Phys. Rev. D 2, 1759-60 (1970).
8. R. Espinoza, T.D. Imbo and M. Satriawan: Identicality, (In)distinguishability and Quantum Statistics. In preparation and UIC preprint (2003).


# Interaction-Free Measurements (Elitzur–Vaidman, EV IFM)

*Lev Vaidman*

The interaction-free measurements proposed by Elitzur and Vaidman [1] (EV IFM) is a quantum mechanical method to find an object that interacts with other systems solely via its explosion without exploding it. In this method, an object can be found without “touching it”, i.e. without any particle being at its vicinity.

The basic idea of the method is as follows. A quantum test particle is being split into a ► superposition of two separated states. One of these states is being split again into a superposition of two output states while the other is being split into a (different) superposition of the same output states. The phases of the various parts are tuned in such a way that there is a destructive interference at one of the outputs. At this output there is a detector. This is the EV device ready for action.

The simplest EV device is the Mach–Zehnder interferometer, Fig. 1. To use it, the device should be placed in such a way that only one of the intermediate states

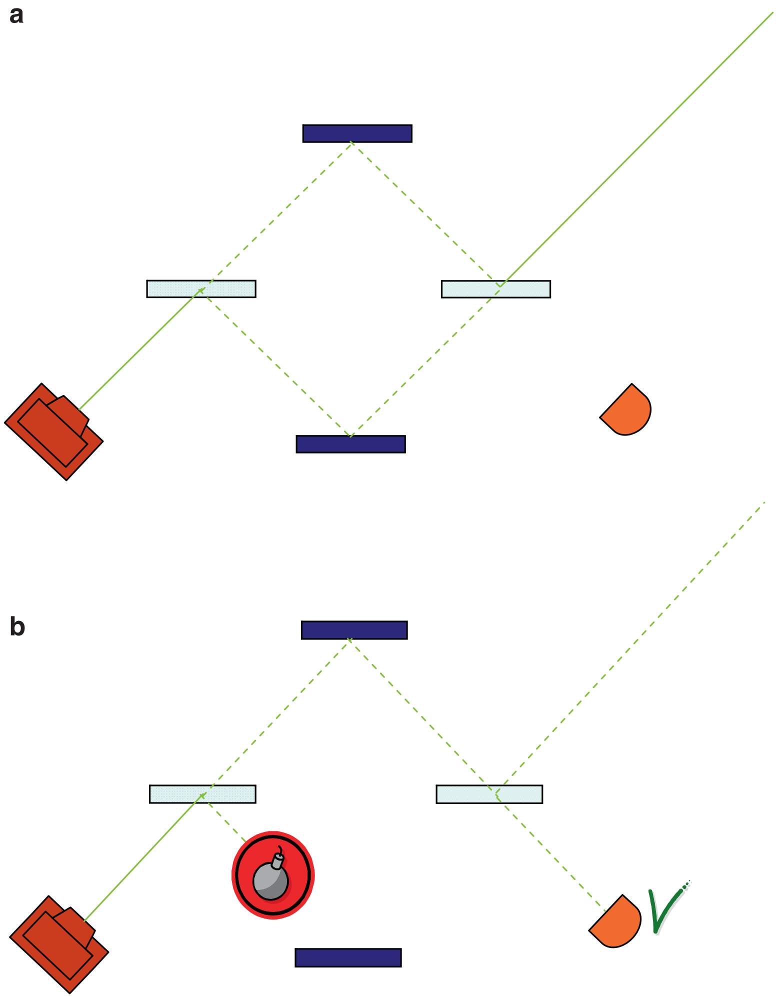


**Fig. 1** The Elitzur–Vaidman scheme (**a**) When the interferometer is empty and properly tuned, photons do not reach the detector. (**b**) If the exploding object is present, the detector has the probability 25% to detect the photon sent through the interferometer, and in this case we know that the object is inside the interferometer without exploding it

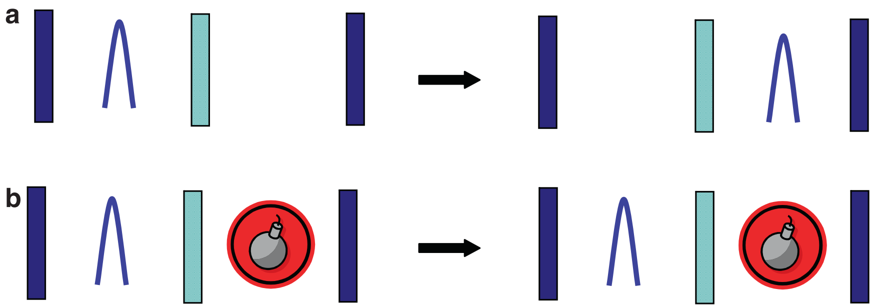


**Fig. 2** The Kwiat et al. scheme. (**a**) If the cavities are empty, the photon after $N$ bouncing moves completely from the left cavity to the right cavity. (**b**) If the object is present in the second cavity, after the same $N$ bounces it will remain in the first cavity with probability close to 1 for large $N$



interacts with the object. If the object is present, the destructive interference is spoiled and the detector might click announcing that the object is present. In this case, no explosion has occurred, since the particle can be found only in one place. The particle can also be "found" by the object, so in half of the cases the object explodes. The probability of finding the object on the first run is just one quarter, so the efficiency of the method is low, but given that the detector clicks, the object is present with certainty.

The EV method was improved using the ► quantum Zeno effect [2] and the probability of the explosion could be made arbitrary small. This, however, requires more time: the quantum test particle has to traverse the interaction region many times. Conceptually, the simplest implementation of this improvement is a device consisting of two identical cavities $A$ and $B$ connected by a highly reflective wall, see Fig. 2. If we place a photon in one cavity, the evolution brings it to another cavity after $N$ bounces in one cavity. At this moment, a detector tests for the presence of the photon in cavity $A$. This is the device which is ready for action. We place it in such a way that the interaction region of possible explosive object is cavity $B$. The detector will click with probability close to 1. (The probability for the failure, which is an explosion of the object, is of the order of $1/N$). It will not click for sure if the object is absent.

Setups similar to the EV device were considered before by Renninger [3] and Dicke [4]. However, they did not realize the effect because in their analysis the object and the test particle were reversed: they pointed out the peculiar property that the EV test particle changes its state while the EV explosive object (their measuring device) has not changed at all, it was a *negative result experiment*.

The EV method can find in an interaction-free manner not only exploding objects, but any opaque object. This experiment, however, is somewhat more difficult to implement. For finding an explosive device we could use, instead of a single particle source, a weak laser beam. If the click happens before the explosion, we know that the object is there. For an opaque object, we need a single particle source: if we get a click sending only one photon, we know that there is a opaque object somewhere inside the interferometer and that it did not absorb any photon.

One of the most paradoxical features of the EV IFM is that the test particle in some sense never passes in the vicinity of the interaction region. How can we get information about a region when nothing passed through it and nothing came out of it? Indeed, when we hear the click announcing the presence of the object, there is no record of any kind in our world showing that the test particle was near the object.

A way to resolve this paradox is to note that of our intuition regarding causality in our world is based on physical laws. These laws, however, describe our Universe which includes many worlds, including the one in which the test particle visited the interaction region (and there was an explosion). In this picture it is easy to understand why there is no interaction free method for finding out that the interaction region is empty. Since there is no parallel world in which an explosion occurs, we cannot verify that the region is empty without passing through it.

Let us consider now what happens when the EV IFM device is used for finding a quantum object. If the ► wave function of the quantum object spreads over space such that only part of it overlaps with the interaction region, the successful EV IFM localizes the object to the interaction region without changing its internal state (without exploding it). The momentum of the object is changed in this procedure. In this respect it is no different from any other nondemolition measurement of the projection on the interaction region. The name "energy exchange free measurement" frequently associated with the EV proposal, thus does not reflect the unique features of the EV IFM [5, 6].

Energy exchange is relevant for the Penrose modification of the EV IFM [5], in which the goal is different: We are to distinguish between objects which explode whenever their trigger is touched and duds where the trigger is locked to the object which do not explode. The dud serves as a mirror in the Mach–Zehnder interferometer which produces a destructive interference in its detector. A good exploding device cannot serve as a mirror and thus the detector might click announcing that the object is not a dud. Penrose's explanation of the core of the IFM is *counterfactual* [7, p. 135]: the object caused the detector to click because it could have exploded, although it did not. This is the origin of the name *counterfactual computation* [8, 9] for a quantum computer which yields the outcome without "running" the algorithm. Note, however, that as we cannot establish the *absence* of an object in an interaction-free manner, we cannot have a counterfactual computation for all possible outcomes [10].

In Penrose's IFM, when the detector clicks, we can claim, as before, that the quantum test particle was not at the vicinity of the exploding object. However, when the EV IFM device is used for finding a quantum object, the click of the detector does not ensure that the quantum test particle was not present in the interaction region. It might that the whole quantum wave of the test particle passes the interaction region. This happens when the observed quantum object is the "test particle" of the EV IFM measuring the presence of the original test particle. This setup is known as Hardy's paradox. This consideration shows that the claim that the EV IFM localizes quantum objects to the interaction region is strictly speaking incorrect. But limitation is minor: anyone observing the location of the object (and not a superposition of localized states) after the EV IFM announcement about its location, will find that EV IFM method is not mistaken.

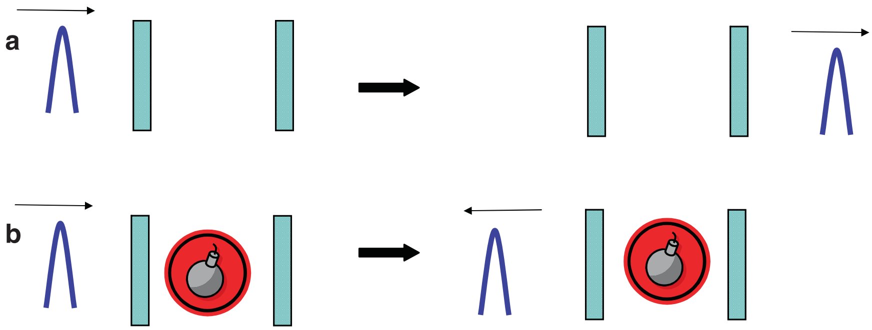


**Fig. 3** The Paul and Pavičić scheme. (**a**) If the cavity is empty, the photon passes through it with very high probability. (**b**) If the object is present in the cavity, the photon is reflected with very high probability



There have been numerous experiments performing the EV IFM. The original EV scheme was first implemented in laboratory by Kwiat et al. [2]. (▶ Quantum Interrogation) Later, Kwiat et al. also performed an experiment of their improved scheme which combines the EV setup with the Zeno Effect [12] reaching efficiency of about 70%. Technical problems make further improvement difficult. It is not easy to tune the optical cavities and it is very difficult to put the photon into the first cavity at a particular moment for starting the process.

When the goal is a practical application of the EV IFM, the best approach is the Paul and Pavičić setup [13] which is, essentially a Fabry Perot interferometer, Fig. 3. There is only one cavity build with almost 100% reflecting mirrors, which is tuned to be transparent when empty. If, however, there is an object inside the cavity, it becomes almost 100% reflective mirror which allows finding the object without exploding it. The method has a conceptual drawback that in principle the photon can be reflected even if the cavity is empty, thus, detecting reflected photon cannot ensure presence of the object with 100% certainty. But this drawback has no meaning for actual experiment because noise in an ideal setup is usually larger. This method was first implemented in a laboratory by Tsegaye et al. [14] and recent experiment reached the efficiency of 88% [15]. The method has a potential to improve controlled-not gate for quantum information processing [16].

Applying the EV device for imaging semitransparent objects [17–19] hardly pass the strict definition of the IFM in the sense that the photons (▶ light quantum) do not pass in the vicinity of the object, but they achieve a very important practical goal, since we "see" the object significantly reducing the irradiation of the object: this can allow measurements on fragile objects.

The EV IFM is one of the quantum paradoxes (▶ Errors and Paradoxes in Quantum Mechanics. It is a task which cannot be performed in the realm of classical physics, but can be done in the framework of quantum theory. Progress in experimental demonstrations of the method shows that it has a potential for practical applications. See also ▶ Quantum Interrogation.

## Primary Literature

1. A. C. Elitzur, and L. Vaidman, Found. Phys. **23**, 987 (1993).
2. P. Kwiat, H. Weinfurter, T. Herzog, A. Zeilinger, and M. Kasevich, Phys. Rev. Lett. **74**, 4763 (1995).

## Secondary Literature

3. M. Renninger, Z. Phys. **136**, 251 (1953).
4. R. H. Dicke, Am. J. Phys. **49**, 925 (1981).
5. L. Vaidman, Found. Phys. **33**, 491 (2003)
6. R. Penrose, *Shadows of the Mind*, p. 240 (Oxford University Press, Oxford, 1994).
7. See Counterfactuals in Quantum Mechanics, in this volume, pp. 132–6.
8. G. Mitchison, and R. Jozsa, Proc. R. Soc. Lond. A **457**, 1175 (2001).
9. O. Hosten, M. T. Rakher, J. T. Barreiro, N. A. Peters, and P. G. Kwiat, Nature, **439**, 949 (2006).
10. L. Vaidman, Phys. Rev. Lett. **98**, 160403 (2007).
11. L. Hardy, Phys. Rev. Lett. **68**, 2981 (1992).
12. P. G. Kwiat, A. G. White, J. R. Mitchell, O. Nairz, G. Weihs, H. Weinfurter, and A. Zeilinger, Phys. Rev. Lett. **83**, 4725 (1999).
13. H. Paul, and M. Pavičić, J. Opt. Soc. Am. B **14**, 1275 (1997).
14. T. K. Tsegaye, E. Goobar, A. Karlsson, G. Bjork, M. Y. Loh, and K. H. Lim, Phys. Rev. A **57**, 3987 (1998).
15. N. Namekata, and S. Inoue, J. Phys. **B 39**, 3177 (2006).
16. M. Pavičić, Phys. Rev. A **75**, 032342 (2007).
17. J. S. Jang, Phys. Rev. A **59**, 2322 (1999).
18. G. Mitchison, and S. Massar, Phys. Rev. A **63**, 032105 (2001).
19. H. Azuma, Phys. Rev. A **74**, 054301 (2006).

# Interpretations of Quantum Mechanics

See ► Consistent histories, Ignorance interpretation, Ithaca Interpretation, Many Worlds Interpretation, Modal Interpetation, Orthodox Interpretation, Transactional Interpretation.

# Invariance

*K. Mainzer*

Invariance, in general, means that quantities or objects do not change with respect to transformations [7]. Invariance of quantities and objects can be distinguished from ► covariance which refers to form invariance of laws and equations [8]. In mathematics, a function of coordinates is called invariant with respect to a transformation