In “interaction free” measurements, one typically wants to detect the presence of an object without touching it with even a single photon. One often imagines a bomb whose trigger is an extremely sensitive measuring device whose presence we would like to detect without triggering it. We point out that all such measuring devices have a maximum sensitivity set by the uncertainty principle, and thus can only determine whether a measurement is “interaction free” to within a finite minimum resolution. We further discuss exactly what can be achieved with the proposed “interaction free” measurement schemes.

In a highly influential recent paper by Elitzur and Vaidman, it was pointed out that the presence of an object (often called a “bomb”) can often be discerned without it absorbing even a single photon. This “interaction free measurement” scheme and later improvements on it have received a lot of attention, both in the popular press as well as in serious scientific journals. In this paper we wish to re-examine such measurement schemes and consider how they may be limited by the Heisenberg uncertainty principle.

We would like to be very precise about what we mean by an “interaction free” measurement, and we attempt to define this in terms of a specific bomb detection experiment. We imagine that the bomb we wish to detect has a trigger that is so sensitive that it will explode if interacts in any way with any particles that are sent to probe it — i.e., if it scatters or absorbs any of these particles. This bomb trigger should be sensitive to an arbitrarily small momentum transfer from the probe particle to the bomb, as well as being sensitive to angular momentum transfer, energy transfer, and transfer of any other quantum number we could consider. We now imagine that some gnome challenges us to determine if he/she has placed this sensitive bomb within some predetermined region (denoted by the dotted box in Fig. 1). If we succeed in detecting the presence of this bomb without blowing it up, we will have performed an “interaction free” measurement. We note, however, that the measurement can only be declared to be “interaction free” if the bomb is truly an ideal detector. If the bomb trigger is unreliable, then we will never know if we have interacted with the bomb or not (This will become important below).

Performing an interaction free measurement as defined above may seem impossible at first — and indeed, within classical physics such a thing would clearly be forbidden. However, by exploiting wave-particle duality, a number of groups have suggested that such measurements are in fact possible. Below, we will discuss the simplest of these proposed measurement schemes, and our results will apply more generally. In this paper we will point out that these schemes in fact do not satisfy the definition of “interaction free” given above. We then continue on to ask ourselves what precisely is achieved by these schemes. In particular, we will show that schemes can indeed claim to be “energy exchange free” (as first discussed in Ref. 4) or free from transfer of certain other quantum numbers, but are not free from transfer of all quantum numbers. Specifically, we will show that such experiments are not free of momentum transfer (although they can be made to have “minimal” momentum transfer).

FIG. 1. The Mach-Zehnder Interferometer. Beam Splitters have reflectivity of 50%. When the beam-line is clear, the interference is arranged such that all of the incoming light exits toward detector B (bright) and none of it exits toward detector D (dark). When the upper beam-line is blocked by an object, 50% of the incoming photons are absorbed by the object, 25% of the incoming photons exit towards detector B, and 25% exit towards detector D. Thus, if we do the experiment with a single photon, and if we happen to detect that photon at detector D, then we know that the object is blocking the beam-line even though the object has not absorbed a single photon.

We begin by discussing the simplest so-called “interaction-free” measurement scheme. As described above, we will think in terms of a bomb detection experiment. The scheme for detecting the bomb, originally proposed by Elitzur and Vaidman, is to construct a Mach-Zehnder interferometer as shown in Fig. 1. We arrange the length of the arms of the interferometer to be such that the interference is constructive when a photon exits...
towards detector B (for bright) and destructive when it exits toward detector D (for dark). Thus, so long as the beam lines are not blocked by any objects, all of the light that enters the interferometer exits towards detector B.

Now we consider what happens when the gnome places the bomb in the predetermined region (i.e., in the dotted box in Fig 1) such that the bomb blocks the beam-line and prevents interference of the two paths of light. For the moment, let us assume that the bomb is in some sense a perfect absorber — an assumption that we will see below has some difficulties. With this assumption, when the bomb is blocking the beam line, 50% of the light sent into the interferometer will be absorbed by the object, 25% will exit towards detector B, and 25% will exit towards detector D. (We have also assumed here that our beam splitters have a reflectivity of 50%). We then send a single photon into the interferometer. 50% of the time this photon will be absorbed by the bomb and it will explode. However, 25% of the time, we will detect the photon at detector D, which is normally dark, and we will know that the bomb is blocking the beam-line without it having absorbed the photon (Also 25% of the time the photon comes out at detector B which is inconclusive). Thus, in this simple way, we are able to perform what appears to be an “interaction free” measurement at least some fraction of the time. Experiments of this type have indeed been performed (in one case with single photons), albeit with imperfect detectors and with a “bomb trigger” with finite sensitivity.

What we would like to point out in this paper is that there is a fundamental limit on the possible sensitivity of the bomb, and hence the measurement can only be considered “interaction free” to within this limited sensitivity.

In order to understand the source of this limitation, we consider the preparation of the experiment. In order for the gnome to set up the experiment and place the bomb in the pre-arranged region (the dotted box in Fig. 1), he/she must know the position of the bomb to within some uncertainty $\Delta x$. Since there is now a finite uncertainty of position, the bomb must have a momentum uncertainty of $\Delta p = \hbar/\Delta x$. If the bomb were sensitive to momentum changes this small, then it would be triggered by quantum fluctuations (and would therefore be a useless device). Another way to say this is that the gnome would be unable to put the sensitive bomb in place without triggering it.

To make this important point more explicit, we imagine how the trigger of such a bomb might work. Before we do our experiment the gnome places the bomb in the prearranged region (i.e., in the dotted box) in some wave-packet such that $\Delta x$ is known sufficiently well for the gnome to know that the bomb is indeed in this region. After we shoot our photon though the apparatus, the trigger apparatus measures the momentum of the bomb. If the momentum is sufficiently large, then the gnome knows that we must have transferred momentum to the bomb (and the gnome would then make the bomb explode). However, the initial momentum state of the bomb must have an uncertainty of $\hbar/\Delta x$, so the gnome certainly cannot reliably detect if we transfer any momentum less than this amount to the bomb. It is interesting to note that this fundamental limit arises from understanding the measuring device (the bomb trigger) as a quantum mechanical device itself.

Because of this limit on the sensitivity of the bomb, it is clear that no measurement can ever be “interaction free” by the definition given above (i.e., the bomb detection experiment with an infinitely sensitive bomb trigger as defined in the second paragraph of this paper), since any bomb can always recoil a very small amount and this interaction could not be detected. One might object that the reason no experiment fits our above definition is simply because our definition is overly restrictive. This may indeed be the case. (Although we also note that the experiment described above seems a reasonably natural choice in the absence of any prior attempts at a definition). Although our choice of definition is a matter of nomenclature which should not overly concern us, it remains a physically meaningful question to ask “what can be achieved by these so-called interaction free measurement schemes?”

It is clear that in order to actually conduct an experiment similar to that proposed above, we must concede that the bomb will have a sensitivity limit for momentum transfers (although it may remain arbitrarily sensitive to transfers of other quantum numbers). Let us then consider an experiment analogous to that described above, but conducted with a finitely sensitive bomb such that only momentum transfers larger than the order of $\hbar/\Delta x$ will cause it to explode. This modified bomb is now sufficiently insensitive so as not to be triggered by the quantum fluctuations of momentum which are necessarily present due to the uncertainty principle. With such a modified bomb of finite sensitivity, we should not declare that detection of this bomb is truly “interaction free” since we will never know if the bomb has interacted very weakly with a probe particle. Nonetheless, it is certainly true that the above described interferometric measurement scheme (as well as more sophisticated versions of interferometric schemes) can indeed detect the presence of this modified bomb without blowing it up. We might say that this is now a “minimum interaction” measurement (By which we mean, we can detect a maximally sensitive bomb without triggering it).

It is now interesting to ask if there are other, perhaps simpler, methods of detecting this modified — slightly less sensitive — bomb without blowing it up. (i.e., of performing a similar “minimum interaction” measurement). One would only need to arrange to touch the bomb extremely softly to detect its presence, and so long as the transferred momentum remains less than $\hbar/\Delta x$, the bomb will not blow up.

One might guess that we could simply probe such a bomb with very long wavelength photons (or other probe particles), thus using a momentum transfer below the
bomb’s sensitivity limit. One must be careful, however, being that the bomb may still be sensitive to other quantum numbers of the probe particles—such as energy or angular momentum, and the bomb might still explode if it absorbs the long wavelength photon even though the momentum transfer is below the sensitivity limit. In other words, we have pointed out above that the bomb cannot be arbitrarily sensitive to momentum transfers (and we have agreed to make our bomb only finitely sensitive to momentum) but the bomb may still remain arbitrarily sensitive to other properties of the probe particle. Thus, in order to perform a “minimum interaction” measurement, we must arrange that no other quantum numbers of the probe particle are changed in the course of the interaction.

One particularly simple approach to making such “minimum interaction” measurements is to perform a simple small angle scattering experiment. We imagine sending a plane wave of short wavelength light at the bomb (Here, the beam must be a wide enough wave packet to be able to either hit the bomb or diffract around the bomb). For a bomb, assumed to be a perfect absorber, the absorption cross section is on the order of the cross sectional area of the object. However, there is also an elastic scattering cross section for small angle diffraction around the edge of the object (I.e., shadow scattering) that is also on the order of the cross sectional area of the object[4]. Since we must know the position to within some accuracy \( \Delta x \) (we must agree to make our bomb only finitely sensitive to momentum) but the bomb may still remain arbitrarily sensitive to other properties of the probe particle. Thus in order to perform a “minimum interaction” measurement, we must arrange that no other quantum numbers of the probe particle are changed in the course of the interaction.

As a final note, we consider a slight variant of this scattering experiment. Here, we imagine holding the bomb in a very weak harmonic potential well to localize its position. The bomb, being itself a quantum mechanical object, is placed in the ground state wavefunction of the harmonic potential. Again, because its position is known to within some accuracy \( \Delta x \), it has a momentum uncertainty \( \Delta p = \hbar/\Delta x \). We note that the (harmonic oscillator) energy levels of the bomb in the well are discrete and are spaced by an energy of order \( \Delta E = (\Delta p)^2/(2M) \) where \( M \) is the mass of the bomb. If we try to transfer some small momentum less than \( \Delta p \) to the bomb (either by using long wavelength photons or small angle scattering), we would not be able to give the bomb enough energy to reach the next eigenstate of the harmonic well. Therefore, the bomb must remain in the ground state wavefunction and the momentum would be transferred directly to the well itself. Indeed, measuring the excitation state of the bomb in the well is a maximal sensitivity measurement since it can measure momentum transfers of order \( \Delta p = \hbar/\Delta x \) and one could never have a bomb trigger more sensitive than this.

In summary, we have pointed out that all measuring devices have a maximum sensitivity fixed by the uncertainty principle. One can then always perform an “interaction free measurement” (in the sense of determining the presence of the bomb without triggering it) by simply probing very softly with very low momentum transfer (either small angle scattering or long wavelength photons). We believe that a large range of so called “interaction free” schemes may have similar limitations once the quantum mechanical nature of the measuring devices are properly understood.

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region must be small enough such that the bomb will always block the beam-line if placed within this region. In this case, we must have the region on the order of the size of the bomb in the transverse direction, and on the order of the length of the beam line in the longitudinal direction.

The simple Mach-Zehnder interferometer is in some sense a rather inefficient experiment, being that it blows up the bomb quite frequently. We can define an efficiency as $P_d/(P_e + P_d)$ where $P_d$ is the probability of detecting the bomb and $P_e$ is the probability of exploding the bomb. It has been pointed out that by using a multiple reflection geometry equivalent to a resonant cavity, one can make the experiment virtually 100% efficient—in the sense that we almost never blow up the bomb. For our current purposes, however, the simple interferometer will be a sufficient example, and the results will apply more generally.

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