

## **On the edge of quantum reality – probing molecules with intense laser fields**

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University of Reading

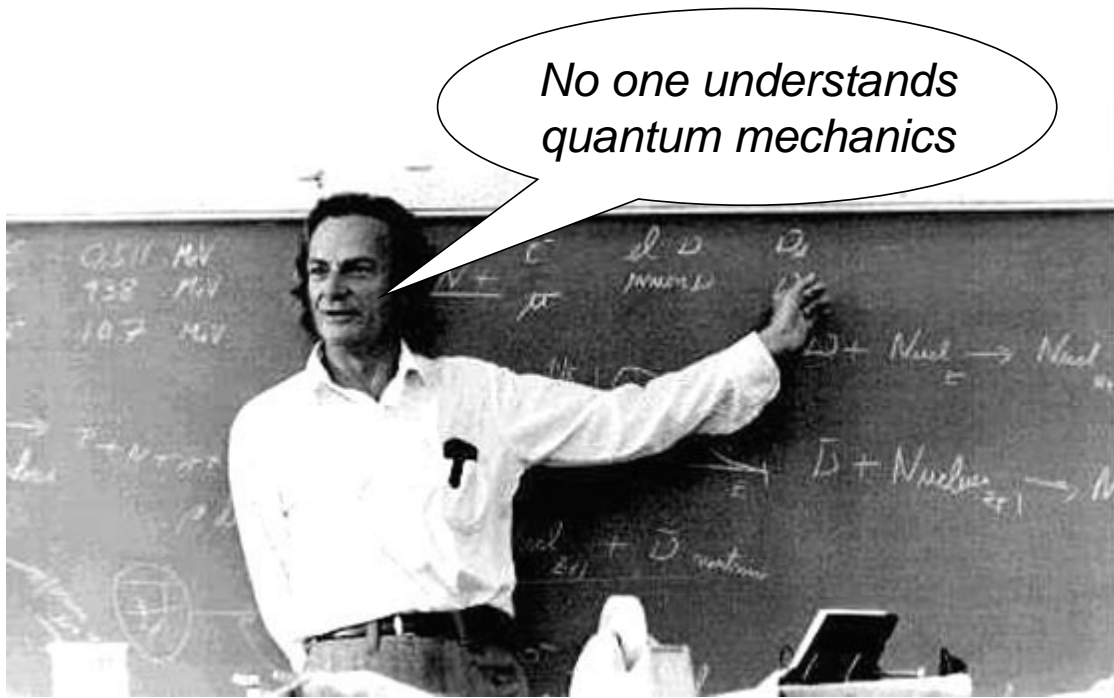
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*Inaugural Lecture, Imperial College London, 25 November 2009*

Thank you Jon for the introduction and thank you all for coming tonight. I'd like to share with you my experience that has kept me on the edge of a fascinating subject throughout of my research career.

I remember well my first encounter with quantum mechanics. It was during my undergraduate studies in Poland. The first year was easy. It was all classical physics and relativity, and my intuition was guiding me smoothly through these subjects. But in the second year I got a surprise – I couldn't understand quantum mechanics! I started to dig in the library and this is what I found...

**Richard Feynman (1918-1988)**



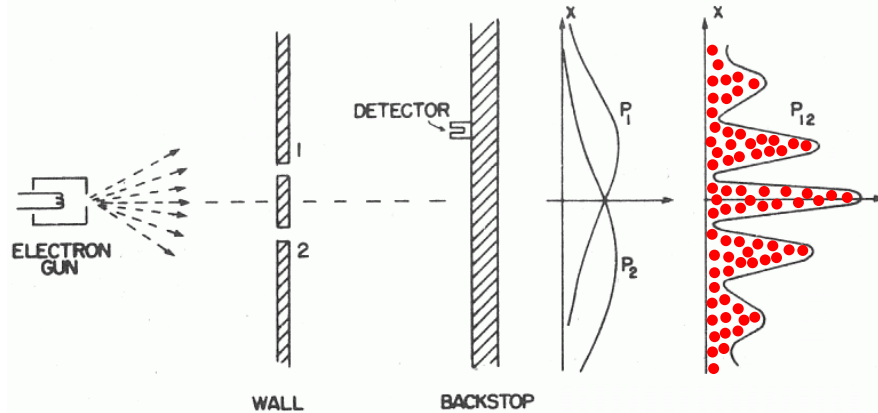
*"The Feynman Lectures on Physics" vol. III*

The answer was in Feynman's lectures recently translated into Polish. I found this unconventional textbook very inspiring. Even today I return to it because some fundamental concepts cannot be found anywhere else.

But what did Feynman mean by saying we cannot understand quantum mechanics?

## Feynman's mystery (1)

In this chapter we shall tackle immediately the basic element of the mysterious behavior in its most strange form. We choose to examine a phenomenon which is impossible, absolutely impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the *only* mystery. We cannot make the mystery go away by “explaining” how it works. We will just *tell* you how it works.

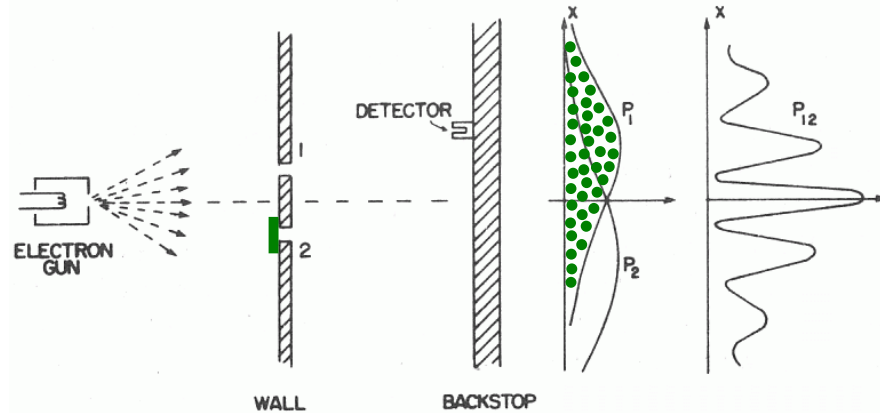


“The Feynman Lectures on Physics” vol. III

To show the fundamental mystery of quantum mechanics Feynman uses the familiar experiment with electron interference. Single electrons come at random from an electron gun, pass through one or the other hole in the wall and fall on a movable detector. The detector records an interference pattern build from single-electron flashes.

## Feynman's mystery (2)

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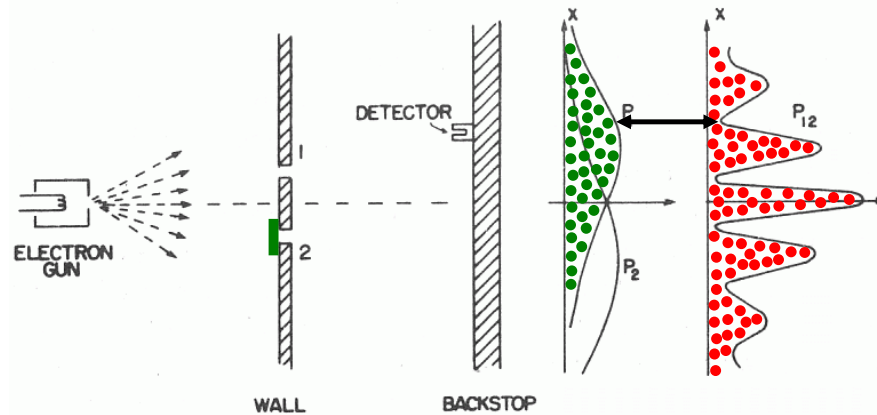


“The Feynman Lectures on Physics” vol. III

But when we block one hole, the interference fringes disappear and the electrons are distributed smoothly. However, this is surprising because where there was a minimum before, now we have more electrons!

### Feynman's mystery (3)

In this chapter we shall tackle immediately the basic element of the mysterious behavior in its most strange form. We choose to examine a phenomenon which is impossible, absolutely impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the *only* mystery. We cannot make the mystery go away by “explaining” how it works. We will just *tell* you how it works.

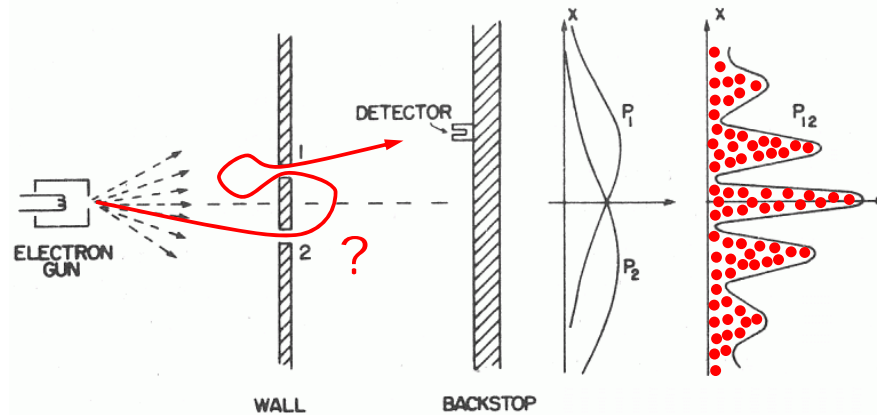


“The Feynman Lectures on Physics” vol. III

How could it be that letting fewer electrons passing through the wall makes more of them to arrive at the detector? Surely the electron must be aware of both holes. Perhaps it can be at two places at once or...

## Feynman's mystery (4)

In this chapter we shall tackle immediately the basic element of the mysterious behavior in its most strange form. We choose to examine a phenomenon which is impossible, absolutely impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the *only* mystery. We cannot make the mystery go away by “explaining” how it works. We will just *tell* you how it works.

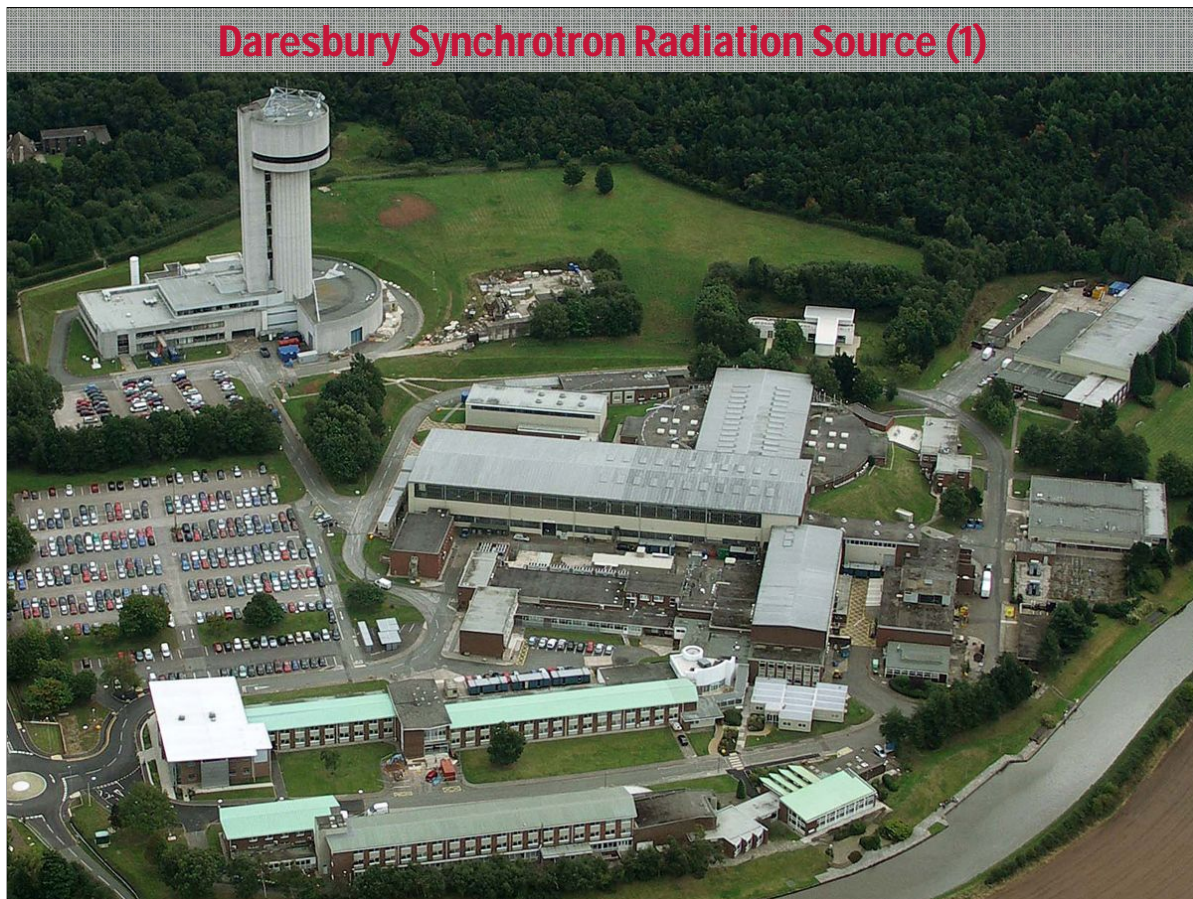


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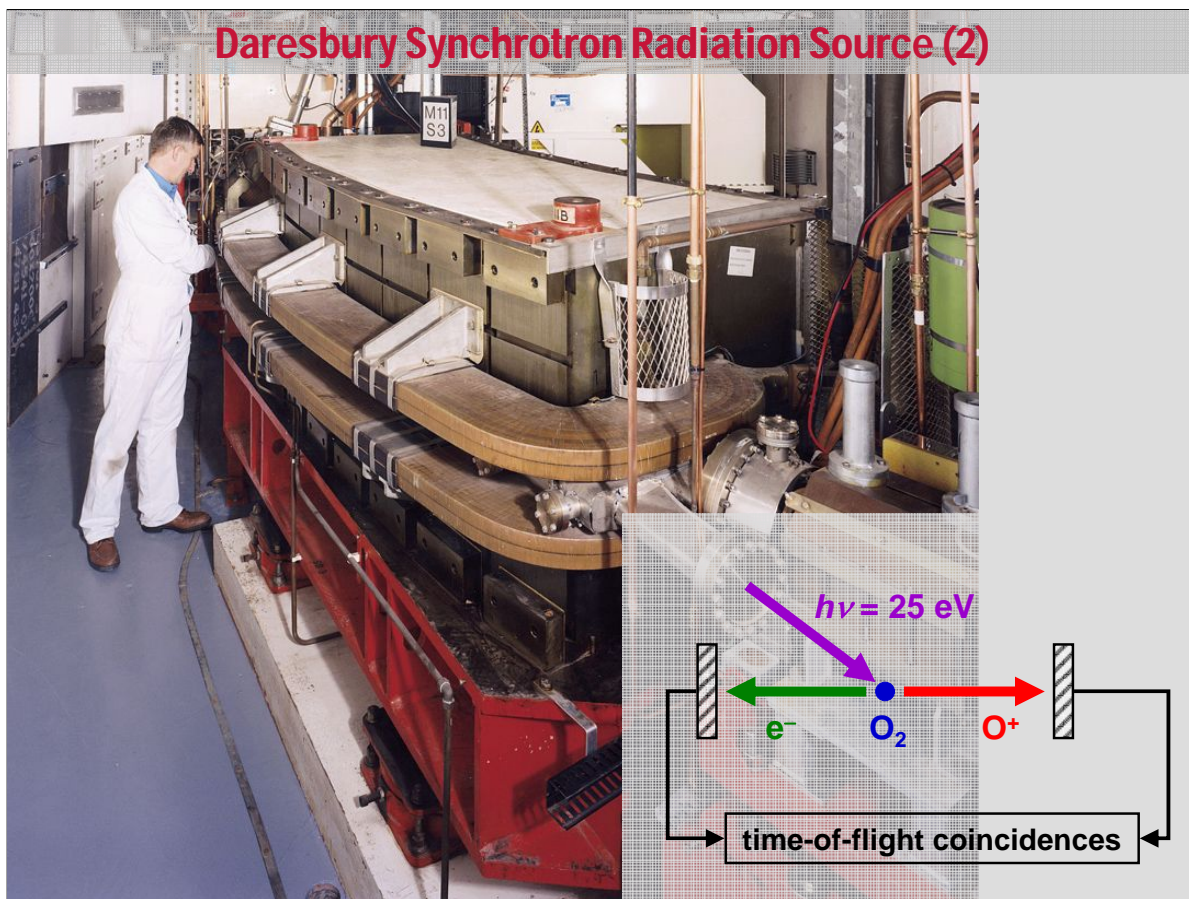
... perhaps it checks both holes before deciding where to go?

What is even more amazing, is that despite this mystery quantum mechanics works. We can use mathematics, for example the Schrödinger equation to predict where an electron can be registered. But what happens before it is registered remains a mystery – this quantum reality is hidden from us.

This mystery, however, had little relevance to my early research.



In 1981 I came to the UK and soon I was fortunate to work at a state-of-the-art laboratory in Daresbury, where I could probe deeply into molecular structure. Inside this building electrons were accelerated to nearly the speed of light and stored in a synchrotron ring.



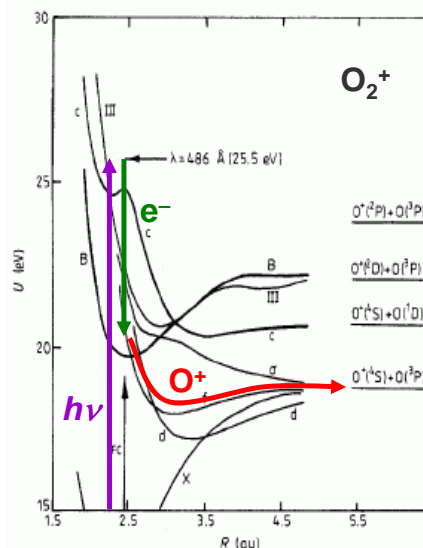
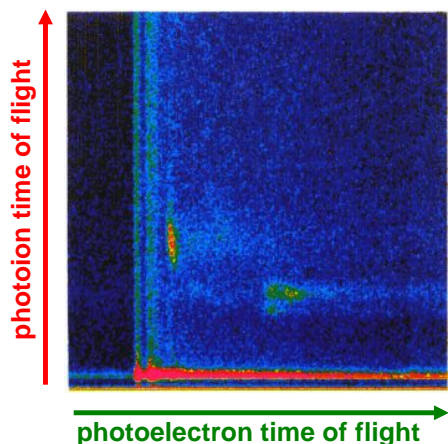
Inside the building we see one of the magnets that keep electrons on the orbit. When the electrons are deflected, they emit synchrotron radiation, which comes out of the tube and is sent through a monochromator to our experiment. In a vacuum chamber a photon strikes a molecule, ionises it and dissociates it. The electron and ions fly apart and we measure their kinetic energies by recording their time of flight from the photon impact to two detectors.

J. Phys. B: At. Mol. Phys. 19 (1986) L819-L824. Printed in Great Britain

LETTER TO THE EDITOR

Dissociative photoionisation of molecules probed by triple coincidence; double time-of-flight techniques

L J Frasinski, M Stankiewicz†, K J Randall, P A Hatherly and K Codling  
J J Thomson Physical Laboratory, Whiteknights, Reading, England



The electron and ion energies tell us how the molecular structure changes during fragmentation. To elucidate this dynamics our group developed a new technique of triple coincidences. I am delighted that most members of our group are here tonight: Keith Codling who led the group, Paul Hatherly who was a PhD student and Marek Stankiewicz who was a visiting researcher from the Jagiellonian University. We used this technique to produce a map.

On this map each dot represents an electron-ion coincidence. After collecting many coincidence points the map reveals the molecular structure. For example, the strongest island is the excited B state of the molecular oxygen ion.

So, the quantum reality seemed accessible: our experimental data did agree with the theory, the fragments did follow these theoretical black curves and Feynman's mystery had little relevance here.

However – as it is often in science – new developments forced me to rethink the meaning of quantum mechanics.

## Femtosecond laser at the Rutherford Appleton Laboratory

Mark Thompson

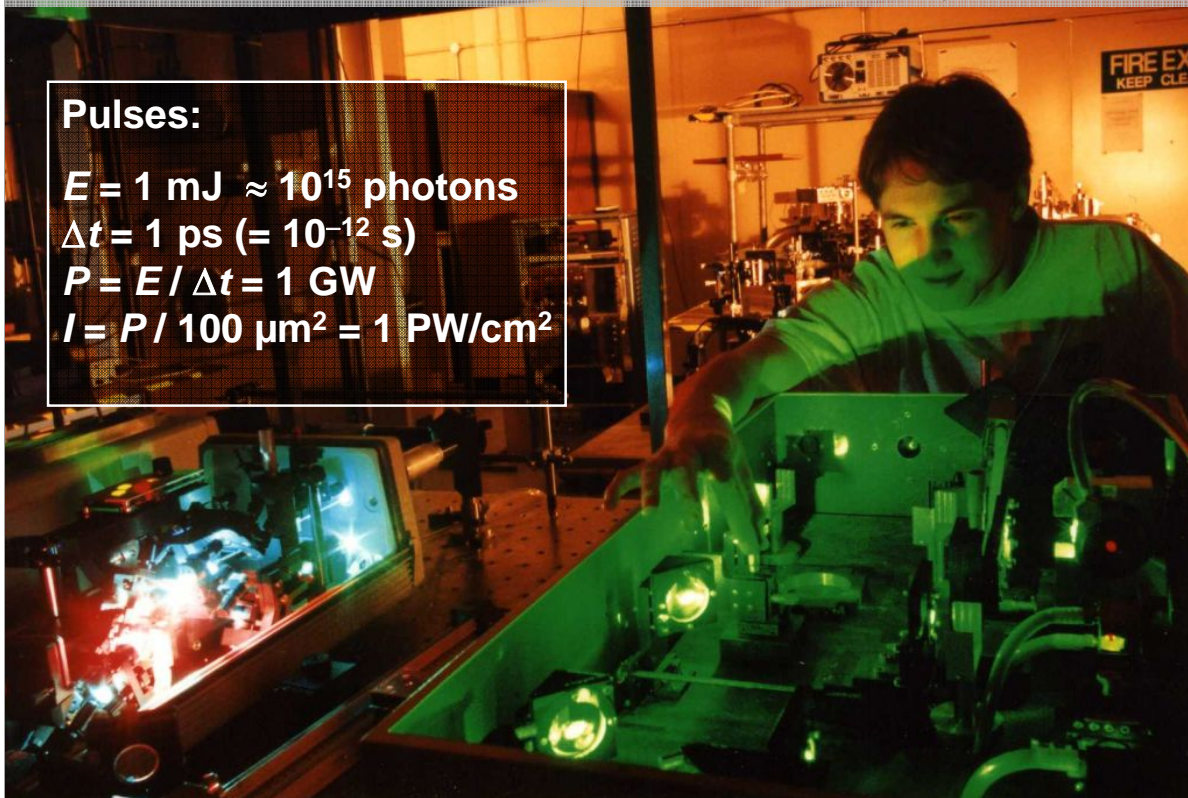
### Pulses:

$$E = 1 \text{ mJ} \approx 10^{15} \text{ photons}$$

$$\Delta t = 1 \text{ ps} (= 10^{-12} \text{ s})$$

$$P = E / \Delta t = 1 \text{ GW}$$

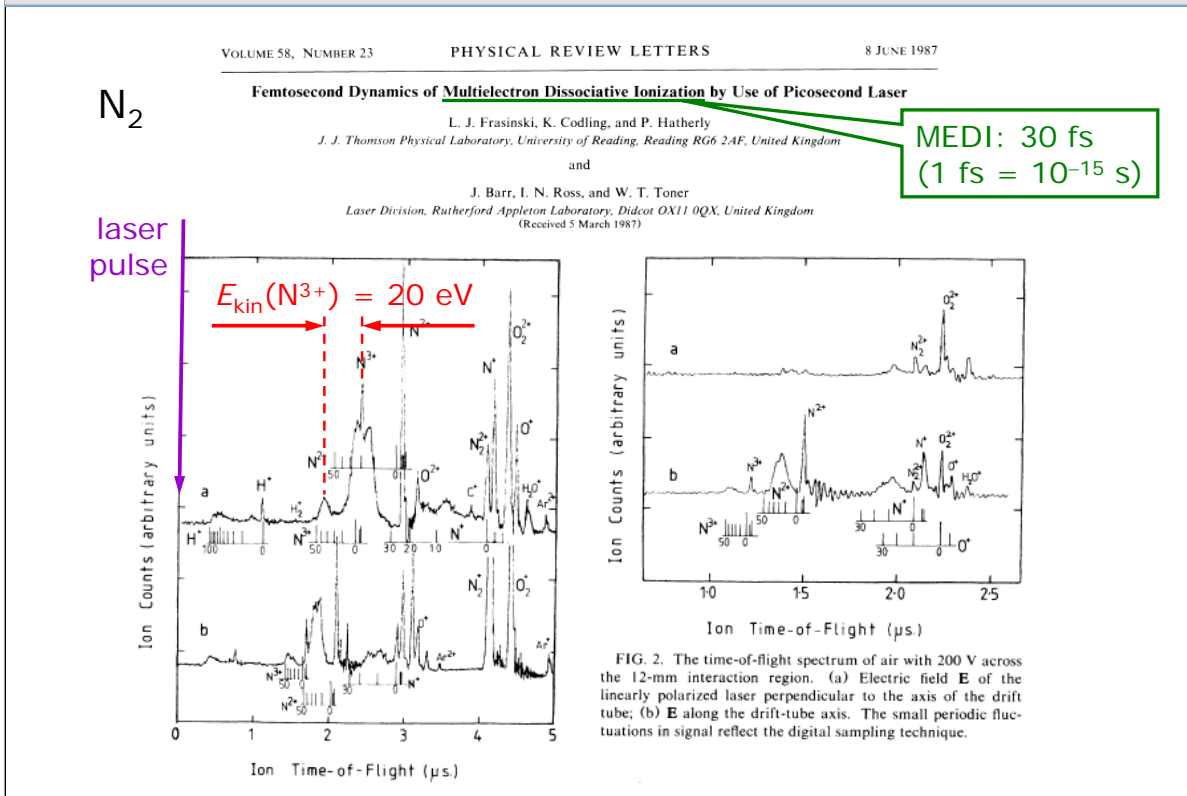
$$I = P / 100 \mu\text{m}^2 = 1 \text{ PW/cm}^2$$



The most significant development was the arrival of ultrafast lasers. Here is my PhD student operating a laser at the Rutherford Appleton Laboratory. This laser produces light pulses of only about a picosecond duration. One picosecond is a long pulse by today's standards but even so, it is so many times shorter than 1 second as one second is shorter than the time that elapsed since the last Ice Age. The pulse energy, 1 mJ, is quite small, so I can safely put my hand in the beam but when concentrated in a short time it can give an instantaneous power of the whole Didcot Power Station. Moreover, we could focus these pulses onto our molecules and illuminate them with intensity million millions times brighter than the surface of the Sun.

In the first experimental run, we studied the fragmentation of hydrogen iodide, which was successful, but the most interesting experiment wasn't planned.

# Multielectron dissociative ionisation



This happened when by accident some air leaked into our vacuum chamber. And here is the time-of-flight spectrum of air we recorded.

At the start of the spectrum the laser pulse ionises and fragments molecules. Then the lighter, multiply charged atomic fragments arrive at the detector and at the longest time of flight are the heavy, singly charged molecular ions of nitrogen and oxygen. Notice that each fragment peak is split into two – this is because the fragmenting molecules eject two groups of ions: initially towards and away from the detectors, and their time-of-flight difference gives us their kinetic energy.

The kinetic energies were very high – and this was a big surprise for two reasons:

- firstly, more than 50 photons had to be absorbed by a single molecule, and
- secondly, these photons had to be absorbed very quickly, before the molecule falls apart: only then we could have two triply ionised nitrogen atoms sitting next to each other to have a strong enough Coulomb repulsion to make them fly apart with high energy.

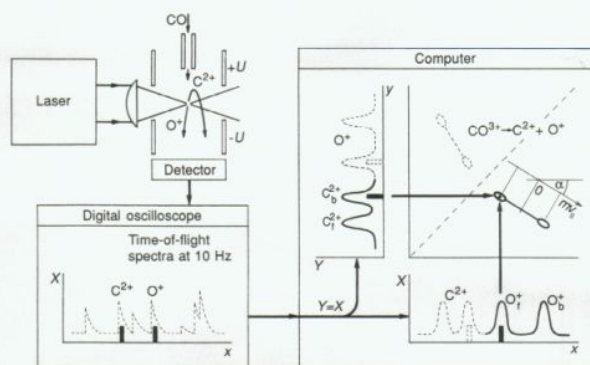
A new, unknown process had to occur on the femtosecond timescale even when the laser pulse was of picosecond duration. It was the apex of many months of hard work – we knew something about nature no one else knew.

Another such moment came a couple years later...

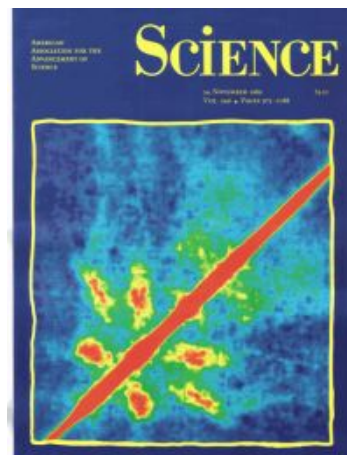
**Covariance Mapping: A Correlation Method Applied to Multiphoton Multiple Ionization**

L. J. FRASINSKI, K. CODLING, P. A. HATHERLY

In some cases there are hidden correlations in a highly fluctuating signal, but these are lost in a conventional averaging procedure. Covariance mapping allows these correlations to be revealed unambiguously. As an example of the applicability of this technique, the dynamics of fragmentation of molecules ionized by an intense picosecond laser are analyzed.



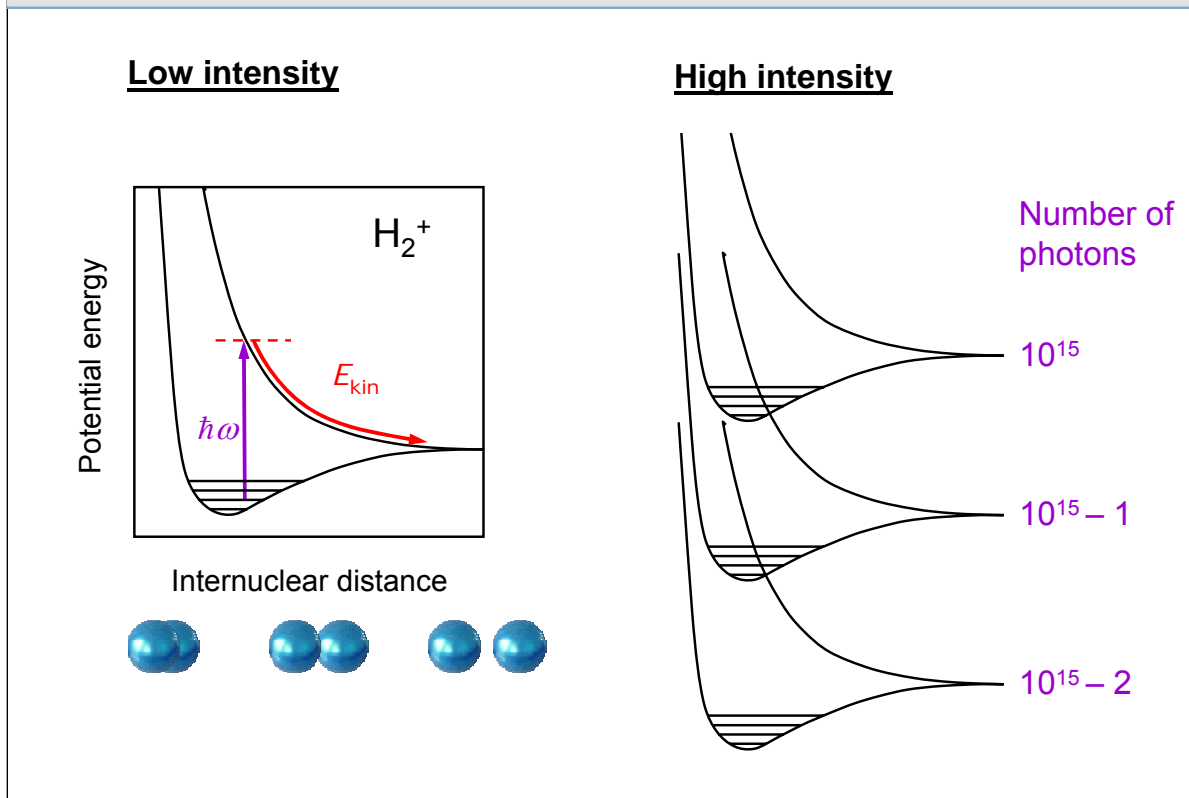
**Fig. 1.** The covariance mapping principle illustrated for a particular ionization and fragmentation channel of carbon monoxide, CO. One can identify the molecular parent ion by correlating the atomic daughter ions. The subscripts f and b denote forward and backward fragment ejection as seen by the detector.



$$\begin{aligned}
 C(x,y) &= \langle (X - \langle X \rangle)(Y - \langle Y \rangle) \rangle = \\
 &= \langle XY \rangle - \langle X \rangle \langle Y \rangle = \\
 &= \langle X(x)Y(y) \rangle - \langle X(x) \rangle \langle Y(y) \rangle \\
 &= \frac{1}{N} \sum_{i=1}^N X_i(x) Y_i(y) - \\
 &= \left[ \frac{1}{N} \sum_{i=1}^N X_i(x) \right] \left[ \frac{1}{N} \sum_{i=1}^N Y_i(y) \right]
 \end{aligned}$$

While the laser research looked very promising, we were still finishing the synchrotron radiation programme and we were left with a lot of experimental time but short of manpower. There were only two people at the experiment: a PhD student and myself but the synchrotron was running 24 hours a day, 7 days a week. After a while my mind was grinding to a halt during the 12-hour shifts. I set the experiment for an automatic data acquisition and went out.

I still remember it was a beautiful sunny day and golden leaves were falling from the trees. But my mind wandered to the laser research and to the problem of unravelling the details the multielectron dissociative ionisation. The problem was that the triple-coincidence technique would not work because there were too many ions produced at each laser shot and we had to use a digital oscilloscope to record the time-of-flight spectra. But then, at this walk, I realised I could send each single-shot spectrum to a computer, put the same spectrum on the x and the y axes, and calculate contributions to covariance represented by the above formula to produce maps of this kind.

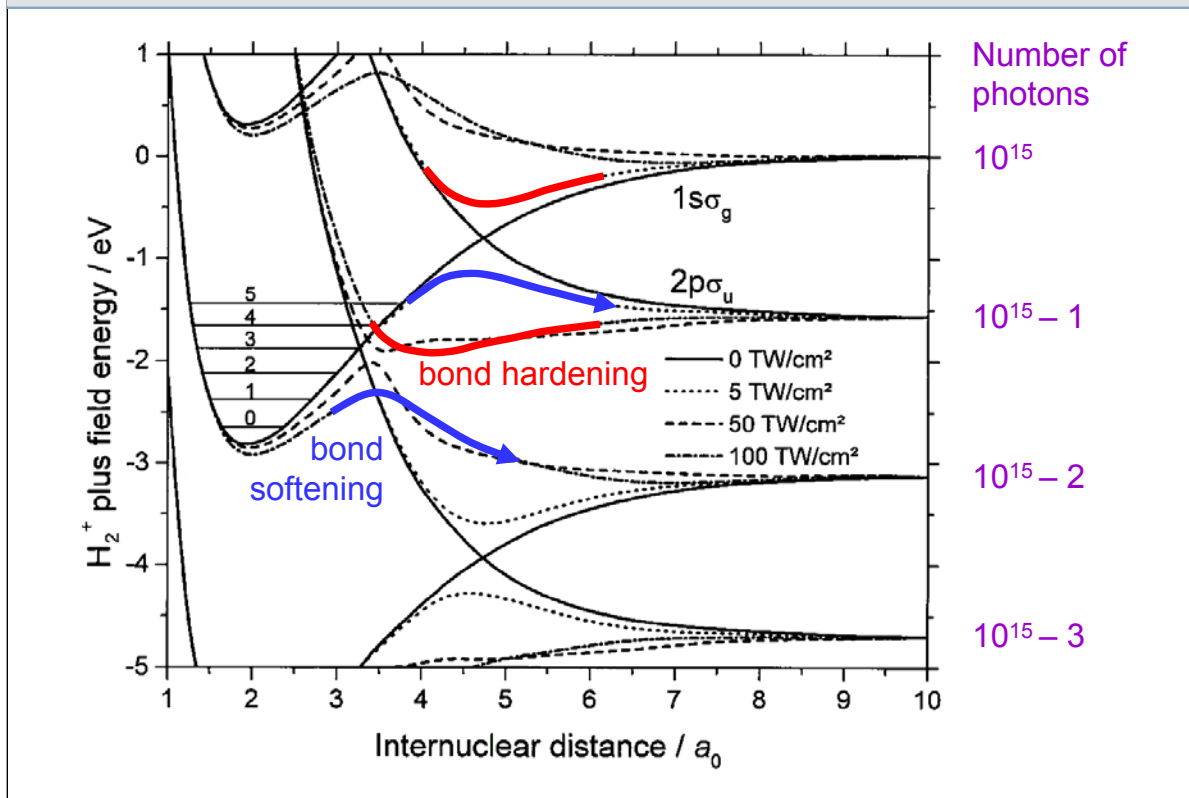


With the covariance mapping technique the quantum reality of molecular dynamics became more accessible but at the same time it was getting complicated.

At low intensity the dynamics is quite simple. Initially the molecule is bound: its internuclear distance is limited by the Coulomb repulsion at the short range and by the chemical bond at the long range. When the molecule absorbs a photon, the binding electron is promoted to a non-binding state and the molecule dissociates releasing kinetic energy. Unfortunately, when we increase intensity these energy curves become distorted.

To describe this distortion at high intensity we have to include all the photons present in the laser pulse. We have a lot of them, around  $10^{15}$  and their number varies, so we have to repeat these energy curves at each field energy:  $10^{15}$  photons,  $10^{15}$  less 1, less 2 and so on. Notice that now the curves cross and a photon absorption corresponds to switching from the bound to repulsive curve at the crossing.

## $H_2^+$ dynamics at high intensity

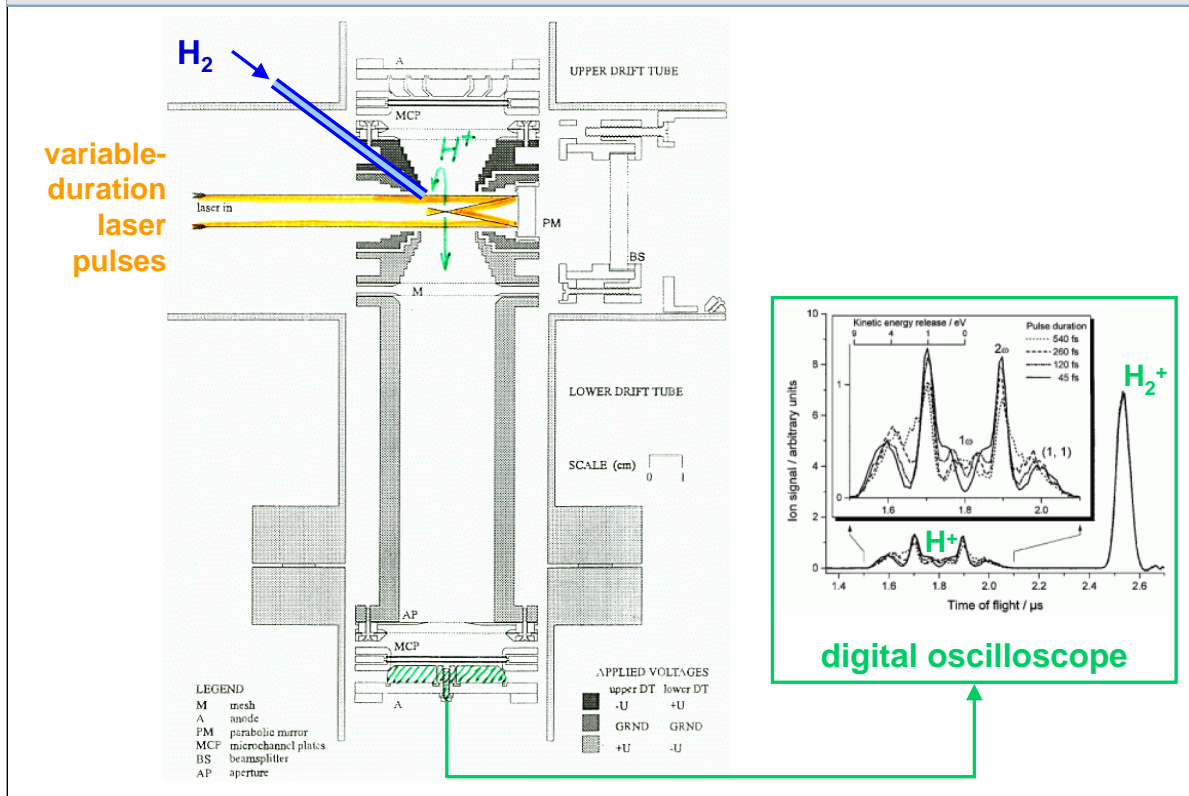


Here are these curves shown again and the picture becomes even more complicated: when we keep increasing the intensity the crossings become anticrossings.

The molecule can now escape along the lower branch of the anticrossing and dissociate. This is called bond softening.

The upper branch forms bond hardening – a new bound state that can exist only in the presence of the laser field. For a long time such states were only a theoretical possibility but our group has proved they really exist.

## Time-of-flight spectrometer



To demonstrate bond hardening experimentally we varied the duration of laser pulses and focused them on a jet of hydrogen molecules. The strong electric field of the laser pulse was fragmenting the molecules and we recorded the time-of-flight of the fragments from the focal spot to a detector on a digital oscilloscope and sent to a computer.

## Signature of bond hardening

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PHYSICAL REVIEW LETTERS

1 NOVEMBER 1999

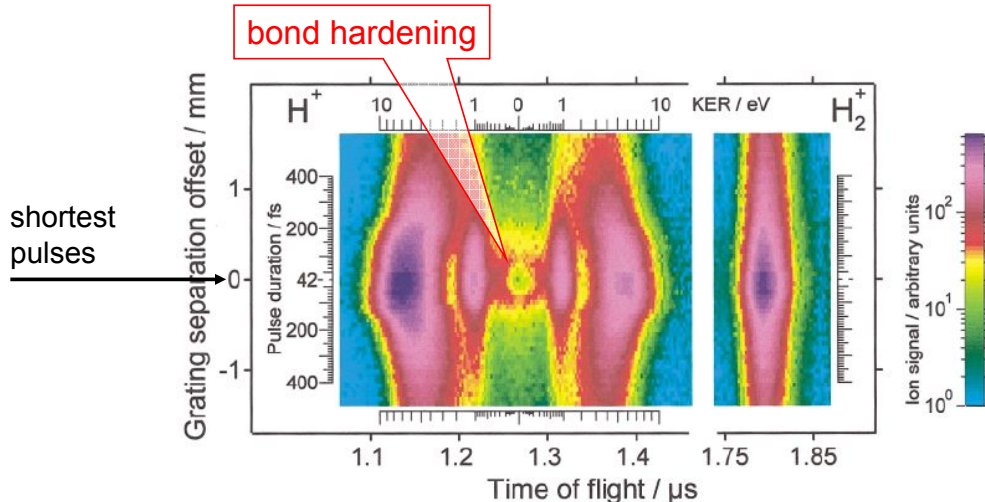
### Manipulation of Bond Hardening in $H_2^+$ by Chirping of Intense Femtosecond Laser Pulses

L. J. Frasinski,\* J. H. Posthumus, J. Plumridge, and K. Codling

*J. J. Thomson Physical Laboratory, The University of Reading, Whiteknights, Reading RG6 6AF, United Kingdom*

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*Central Laser Facility, Rutherford Appleton Laboratory, Chilton, Didcot OX11 0QX, United Kingdom*



The computer was building a time-of-flight map of the molecular ion and protons versus the pulse duration. The pulse is shortest in the centre becomes longer up and down, also with decreasing intensity. You can see several features on the map but the most interesting one is in the centre: this is the signature of bond hardening. You can see that this crater-like feature exist only at the shortest pulse. And the separation of the walls tell us the energy of the protons released from this bond-hardened state. This energy decreases as the pulse is lengthened, which was very puzzling. It took me almost a year to understand what happens here.

## Dynamics of bond hardening

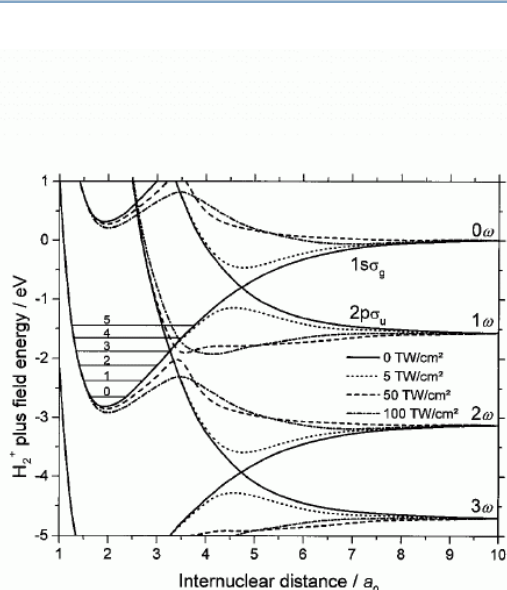


FIG. 2. Molecular potential energy curves of  $H_2^+$  dressed in a photon field of 792 nm wavelength. With increasing laser intensity curve crossings become anticrossings. A nuclear wave packet with kinetic energy corresponding to the 3rd and 4th vibrational levels of a free molecule can be trapped in the potential well created by intensities of 100–200  $TW/cm^2$  at  $4a_0$ .

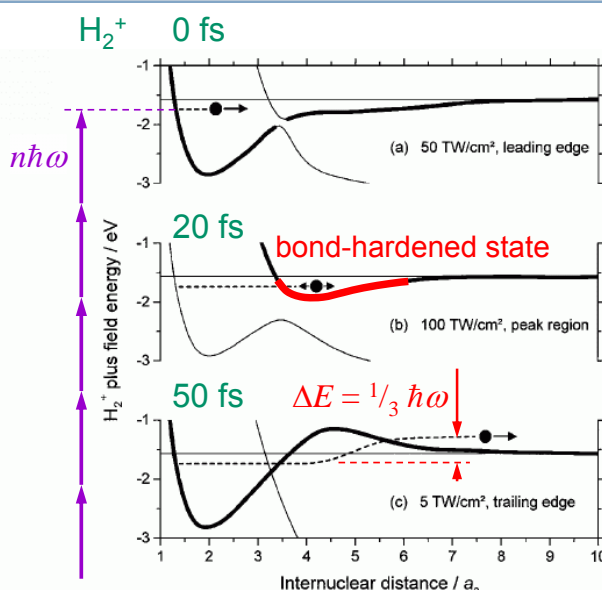


FIG. 3. The dynamics of bond hardening.  $H_2^+$  is created on the leading edge of the laser pulse and the wave packet jumps the anticrossing gap (a). As the intensity increases, the gap widens and the wave packet is trapped (b). Falling intensity flexes the well upwards and the wave packet is released (c). The kinetic energy release depends on the speed of the intensity fall.

So this is what happens.

(a) The molecular hydrogen is ionised and the molecular ion starts to dissociate.

(b) But the intensity increases and the ion is trapped in the bond-hardened state. This trapping lasts only as long as the laser field lasts – a few tens of femtoseconds.

(c) When the pulse is gone, the molecular curve flips up to its original shape and lifts the ion to a higher energy before it dissociates. The faster the laser pulse disappears, the quicker is the flipping up and the higher is the energy transferred to the ion.

But this energy can be a fraction of the photon energy. Look! Here about 1/3 of a photon has been absorbed from the laser field. How could it be? Can we have fractions of a photon?

## Are photons real particles?

Appl. Phys. B 60, 77–84 (1995)

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Physics B** Lasers  
and Optics  
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### Anti-photon

W.E. Lamb, Jr.

Optical Sciences Center, University of Arizona, Tucson, AZ 85721

Received: 23 July 1994 / Accepted: 18 September 1994

**Abstract.** It should be apparent from the title of this article that the author does not like the use of the word “photon”, which dates from 1926. In his view, there is no such thing as a photon. Only a comedy of errors and historical accidents led to its popularity among physicists

vacuum fluctuations:  $E = \hbar\omega(n + \frac{1}{2})$

number of photons

half a photon?

### Optics & Photonic News 2003

October 2003 ■ OPN Trends

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photoelectric  
effect  
without  
photons

The answer is quite simple: the concept of a photon is overused. According to Willis Lamb “there is no such thing as a photon. Only a comedy of errors and historical accidents led to its popularity”. These words cannot be ignored easily because they come from a Nobel prize winner who has shown the reality of vacuum fluctuation represented by the following formula.

If  $\hbar\omega$  is the quantum of electromagnetic energy and  $n$  is interpreted as the number of photons then surely we should say that the vacuum fluctuations are made of halves of photons!

The discussion still continues on what a photon is. In this quite recent review you can find, for example, how to explain the origin of quantum mechanics without photons. The inescapable conclusion is that photons are quasi particles, like phonons or electron holes in a semiconductor. A photon seems to be a less real particle than, for example, an electron.

But what does it mean “less real”? Isn’t reality something that is or isn’t there? Can we have degrees of reality? To answer these questions let us remind ourselves how we discover reality.

**Geocentric**

**Heliocentric**

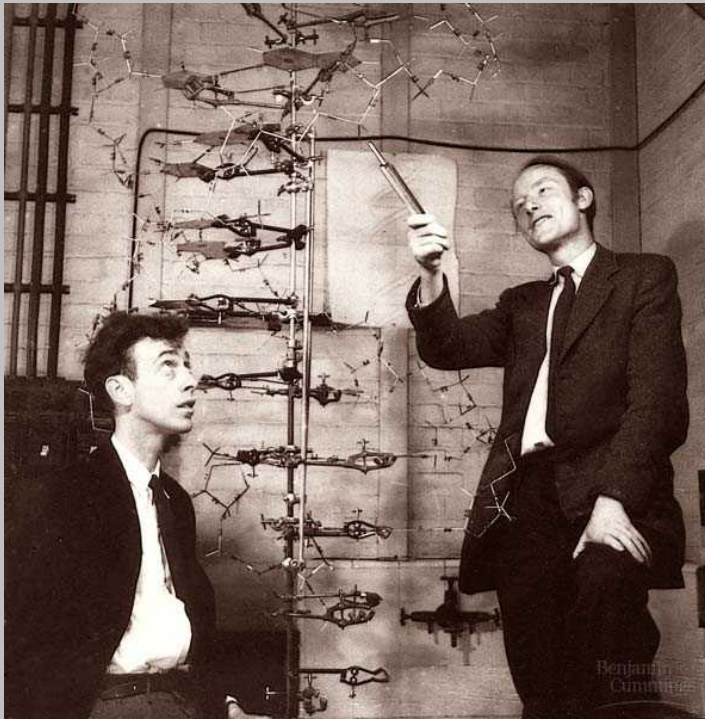


Andreas Cellarius Palatinus "Atlas Coelestis seu Harmonica Macrocosmica" Amsterdam 1661

We discover reality by constructing models. I've chosen this example from a beautiful 17<sup>th</sup> century atlas because I studied physics and started my research at one of the oldest universities, the Jagiellonian University in Kraków. At the same university 500 years ago Nicolaus Copernicus was a student. He rejected the geocentric model of the Universe and said that the Earth revolves round the Sun.

Today, the geocentric model is considered to be false, but I wouldn't be so strong about it. It is perfectly adequate for everyday purposes, for example when we want to know if it is dark now in Tokyo. We use the heliocentric model only in special cases, for example, when we want to send a rocket to Mars.

Five hundred years ago you may be burned at the stake for picking the wrong model but today we have the freedom of choice, which is also available at the molecular level.



James Watson and  
Francis Crick with  
their DNA model

Here is the original model of the DNA molecule constructed by James Watson and Francis Crick in 1953. Even with an enormous success of this model in molecular biology, genetics and medicine, it represents only a crude approximation at the fundamental level.

He



1. Simple atom

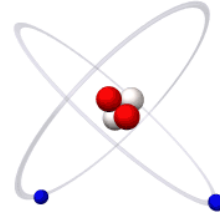
Let us look closer at this approximation using a simple example of a helium atom. From the point of view of molecular modelling the helium atom is just a small ball. It is far too simple for a physicist who is interested in the atomic structure.

## Which model? (2)



1. Simple atom

2. Classical physics



We know that inside the helium atom there are two electrons orbiting the nucleus. This model is better, but it is still approximate.

## Which model? (3)

**1. Simple atom**

**2. Classical physics**

**3. Quantum theory**  
6D wavefunction

more dimensions:  
laser field,  
spins,  
nucleus...

The accurate description of the helium atom calls for quantum mechanics. The essence of this description is a wavefunction constructed in an abstract space which has at least 6-dimensions: 3 spatial coordinates of the first electron and 3 coordinates of the second one. Unfortunately our intuition fails to grasp this 6-dimensional model. In fact, any structure beyond our 3-dimensional world is very difficult to envisage. I can't even draw this wavefunction properly here!

This poses a serious problem I first noticed at one of the scientific conferences, where I met a brilliant theoretician who calculated the exact wavefunction for the helium atom. Using some mathematical tricks he was able to reduce the number of dimensions from 6 to 4, but even so he needed a powerful supercomputer to manage the result. When I heard what he had achieved I was enthusiastic. "Isn't it wonderful? You have all the answers many people have been trying to find for years!", I said. But he answered: "Not quite. It is very frustrating: the solution is there, in the computer, but it is too complex. To understand it I have to make it simpler." Then I realised that an accurate solution can be next to useless without a simple model.

## Which model? (4)

**1. Simple atom**

**2. Classical physics**

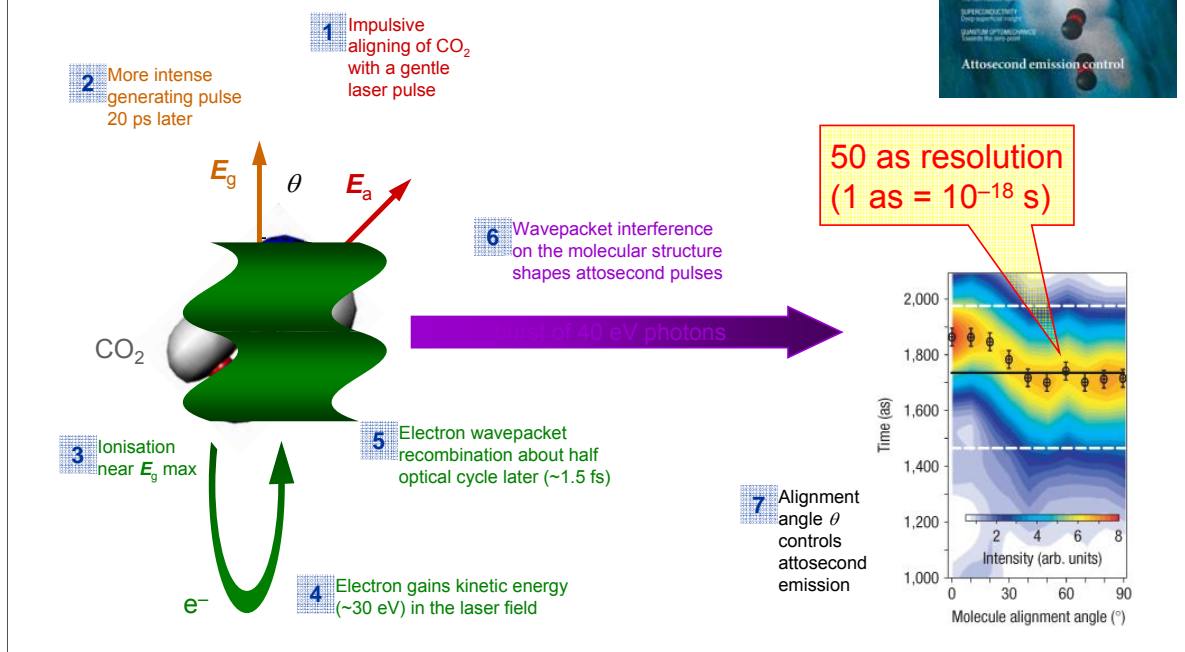
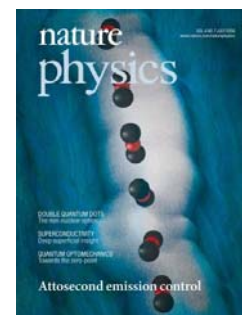
**3. Quantum theory**  
6D wavefunction

more dimensions:  
laser field,  
spins,  
nucleus...

In practice, we construct models which are the best compromise between simplicity and accuracy. Simple models are very useful in probing the complexities of the quantum reality. We have developed a few such models but tonight...

# Coherent control of attosecond emission from aligned molecules

W. BOUTU<sup>1</sup>, S. HAESSLER<sup>1</sup>, H. MERDJI<sup>1</sup>, P. BREGER<sup>1</sup>, G. WATERS<sup>2</sup>, M. STANKIEWICZ<sup>3</sup>, L. J. FRASINSKI<sup>4</sup>, R. TAIEB<sup>5,6</sup>, J. CAILLAT<sup>5,6</sup>, A. MAQUET<sup>5,6</sup>, P. MONCHICOURT<sup>1</sup>, B. CARRE<sup>1</sup> AND P. SALIERES<sup>1\*</sup>



I'd like to outline a very successful model conceived by Paul Corkum from Ottawa. This model is now known as the 3-step model and describes the generation of attosecond pulses, that is pulses that are almost a million times shorter than the laser pulses I used at the beginning of this research.

In the first step the strong laser field removes an electron from an atom or a molecule.

In the second step the laser field accelerates the electron. In this process, however, the laser field oscillates with the optical frequency, so about a femtosecond later the field reverses and the electron returns back to the molecule.

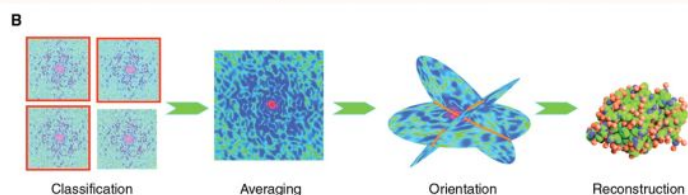
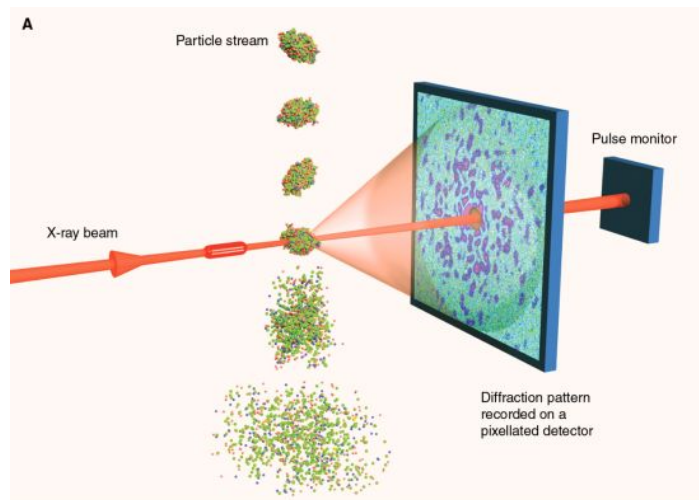
In the third step the electron collides with the molecule and generates a burst of soft X-rays. Due to a very short time of the collision the burst duration is only a few tens of attoseconds.

We used this model to explain our recent experiment where we controlled the timing of this burst with the accuracy of 50 attoseconds.

The aim of this research is to build a kind of electron microscope, where the returning electron can not only resolve single atoms in a molecule but also probe the changes to the molecular structure on the attosecond timescale. Such a microscope would be a powerful tool – it would give chemists an insight into the finest details of chemical reactions.

## Future: X-ray lasers

### Free electron laser in Hamburg

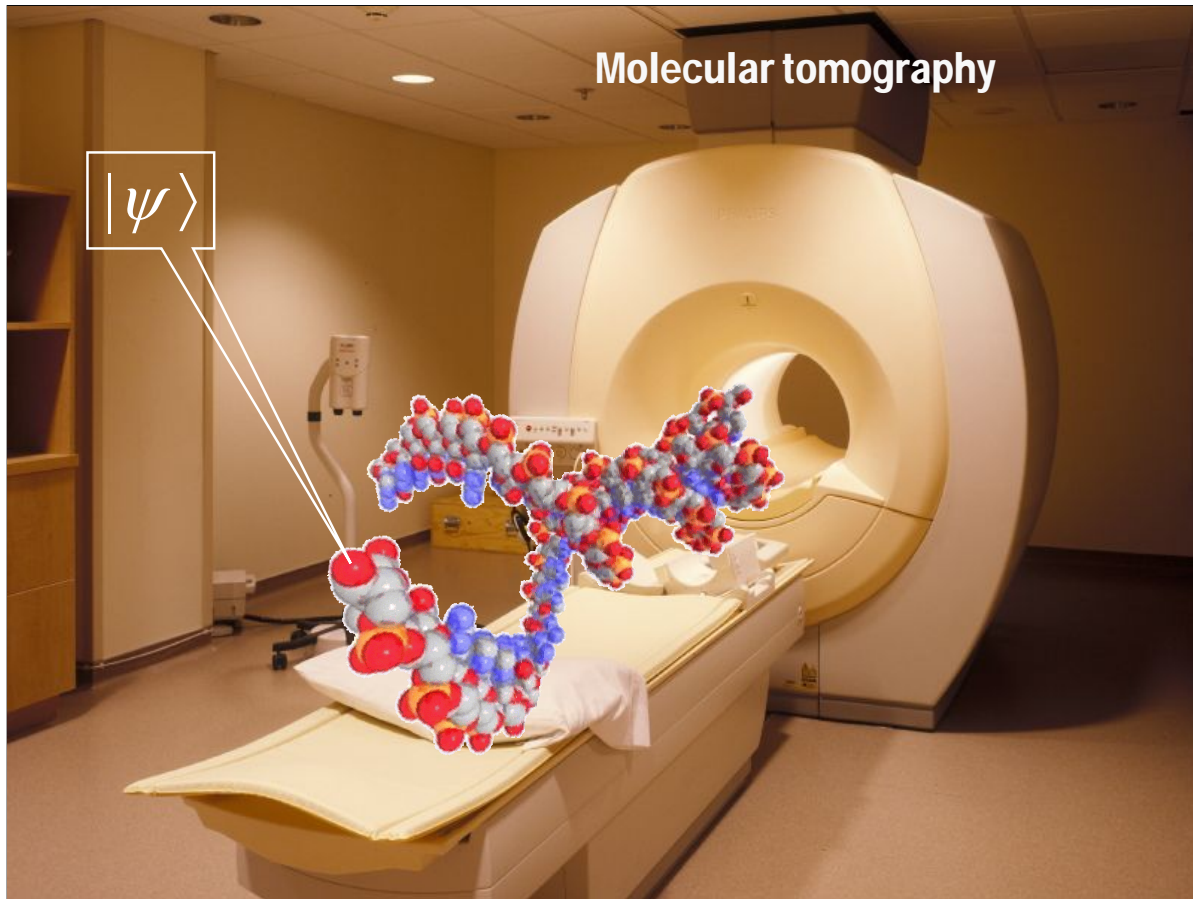


### Imaging Atomic Structure and Dynamics with Ultrafast X-ray Scattering

K. J. Gaffney and H. N. Chapman, *Science* **316** 1444–1448 (2007)

Today's laser technology progresses at a fast pace. Large electron accelerators are used to build x-ray lasers. The principle of their operation is similar to synchrotron radiation. The electron beam is accelerated from the source, wiggles in many magnets and builds up the energy of the x-ray pulses sent to an experimental hall. This laser is only a pilot study for building the full machine, which will be over 3 km long and will extend to the outskirts of Hamburg.

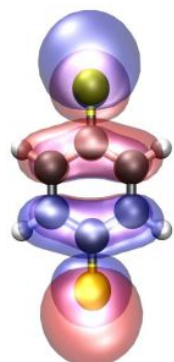
This huge investment is driven by biological applications. X-rays can be used to resolve the structure of large molecules, viruses and organelles. Unfortunately the x-rays damage the sample under study. Reducing the intensity does not help because the sample still decomposes before the information recording is completed. The idea is to do the opposite: hit the molecule with a very short, very intense x-ray pulse. Surely, the molecule explodes but before the explosion even starts, the diffraction pattern is recorded and we have all the information we need. By collecting this information many times, for many different orientations of the molecule, we can effectively perform tomography, for example, of a flu virus.



In the normal tomography we use electromagnetic fields to image 3-dimensional structure of a large object such as human body.

But in the case of the molecular tomography we enter the quantum world and we need to image the wavefunctions. And the wavefunctions bring us back to Feynman's mystery.

## Can we observe the wavefunction?



$$|\psi\rangle = \sum_i c_i |\psi_i\rangle$$

$$P_i = |c_i|^2$$

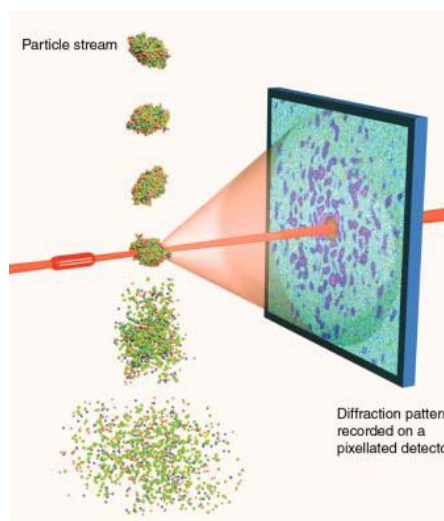
Wavefunction:  
not an observable!

Eigenfunction:  
not an observable!

$$\hat{A} |\psi_i\rangle = a_i |\psi_i\rangle$$

Operator:  
an observable

Eigenvalue:  
observation  
result



Bernard d'Espagnat "Conceptual Foundations of Quantum Mechanics" Perseus Books 1976

The wavefunction has a strange status in quantum mechanics. On one hand if we know the wavefunction, we know everything that can be known about the system. On the other hand it is not an observable. "An observable" is a technical term. In quantum mechanics observables are represented by operators acting on base wavefunctions called eigenfunctions. The action of the operator produces an eigenvalue, which is the result of the observation.

The wavefunction is composed from eigenfunctions but neither the eigenfunctions nor the wavefunctions are observables. So how can molecular tomography work? How can we observe the wavefunctions of molecular structure?

We do it by performing the measurement many times on many identical molecules. Each single measurement gives us only an estimate how to compose the wavefunction but as the number of measurements increases we approach certainty in the wavefunction reconstruction.

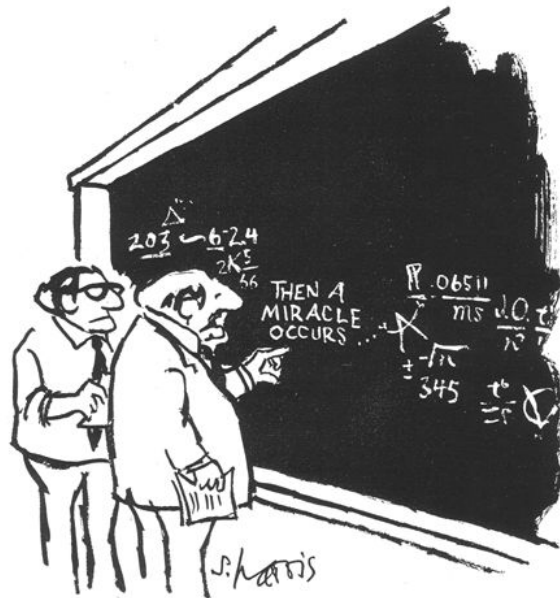
## Wavefunction collapse

$$|\psi\rangle = \sum_i c_i |\psi_i\rangle$$

$$\hat{A}|\psi_i\rangle = a_i |\psi_i\rangle$$

~~$$\hat{A}|\psi\rangle = \sum_i c_i a_i |\psi_i\rangle$$~~

$$\hat{A}|\psi\rangle \rightarrow |\psi_i\rangle$$



"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

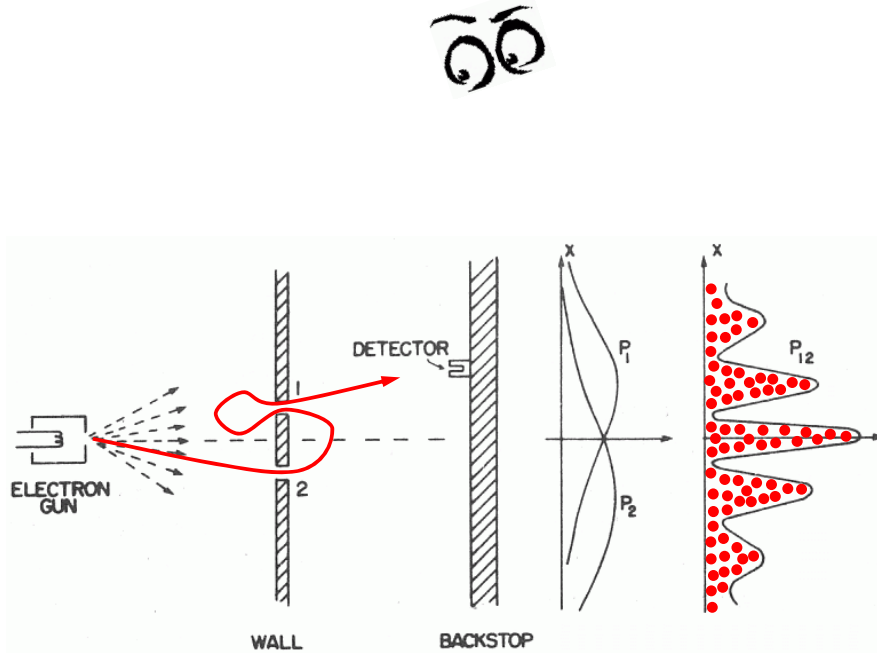
The reason why a wavefunction is not an observable is that the measurement changes it.

You may expect that the measurement leaves the wavefunction in a superposition of eigenfunctions but this is not what happens.

The normal, continuous evolution of the wavefunction, according to the Schrödinger equation, is suddenly discontinued and the wavefunction collapses to only one of the eigenfunctions. It is not clear how to understand this discontinuity. Is the quantum reality truly jumping each time a measurement is performed?

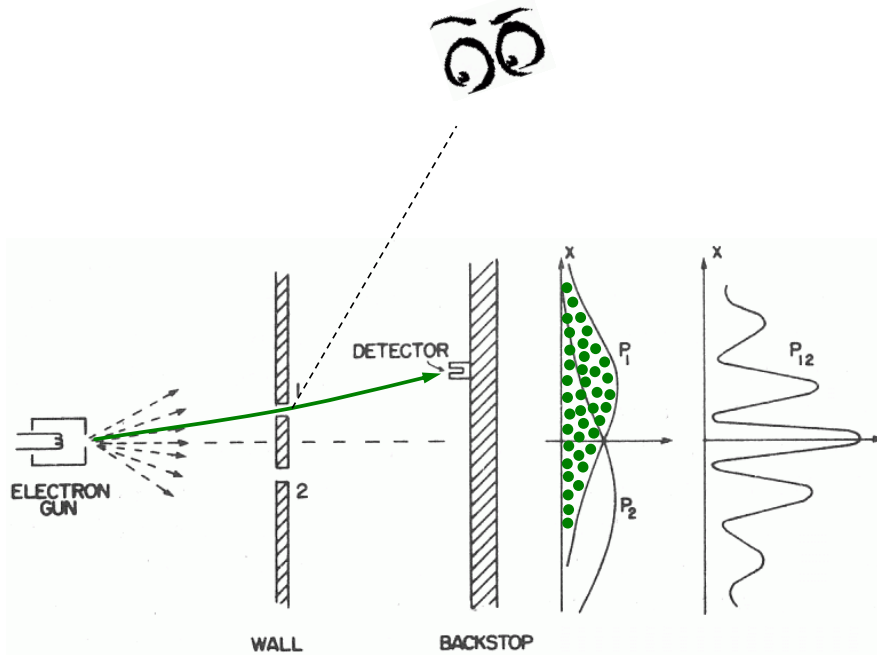
Many textbooks simply postulate that this is the case, but I think we should be more explicit here.

## The measurement problem (1)



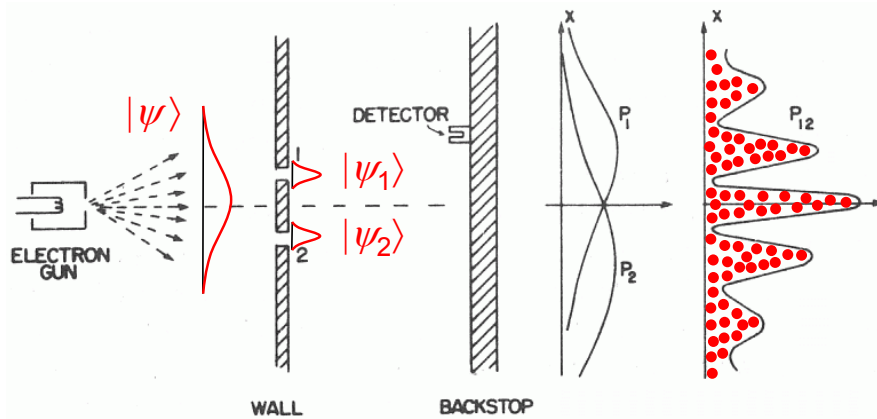
Let me show the problem on the example of electron interference, where we wondered how the electron moves. Suppose that instead of blocking one hole we want to look at the electron.

## The measurement problem (2)



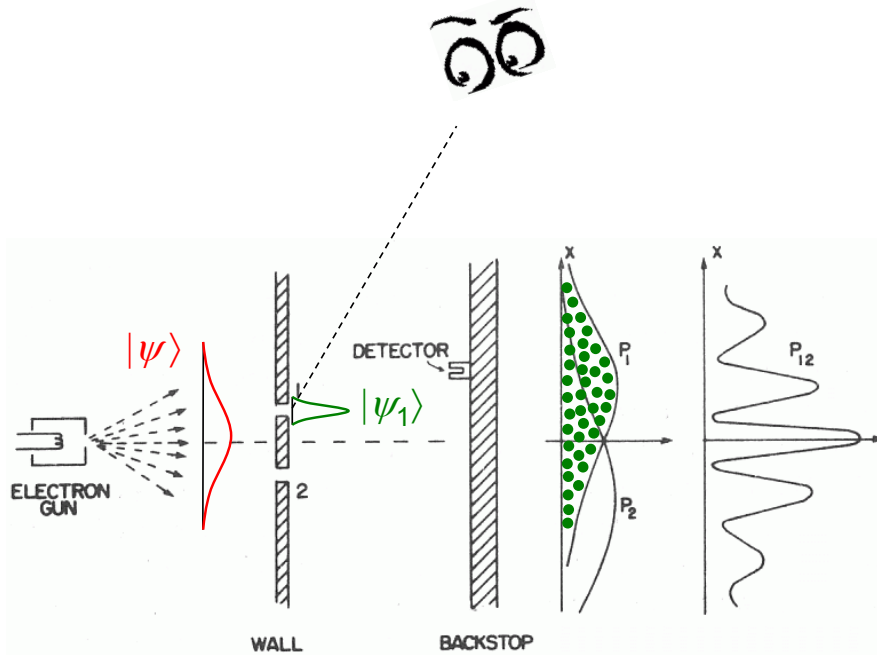
Unfortunately, as soon as we see where the electron is, the interference pattern disappears.

### The measurement problem (3)



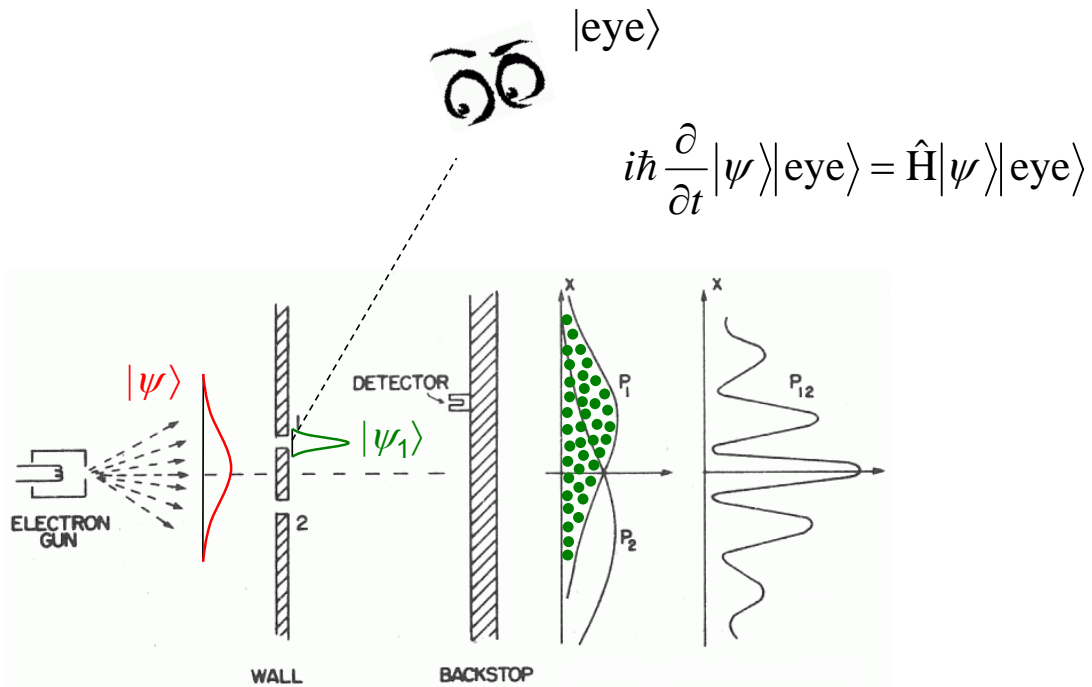
This is because initially the wavefunction spreading from the gun passes through both holes.

## The measurement problem (4)



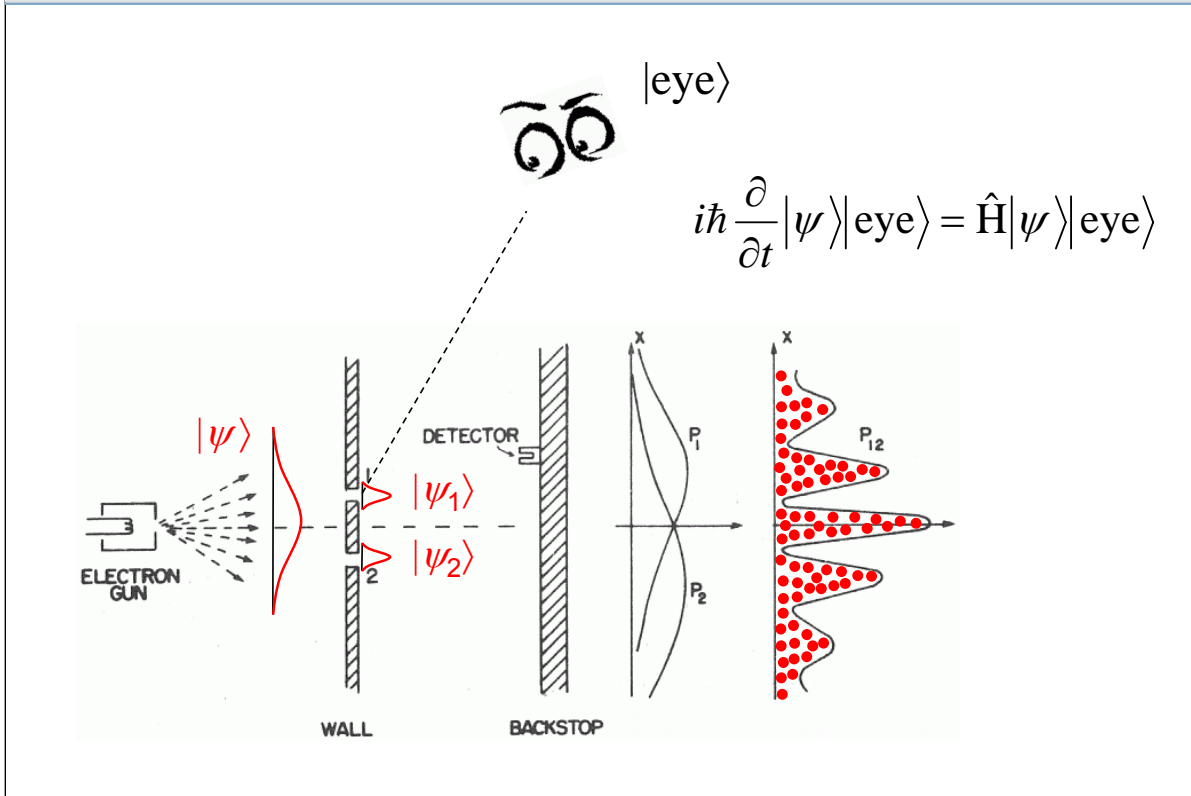
But when we look, it collapses to only one hole – this one which the electron goes through – and the interference pattern disappears.

The measurement problem (5)



However, quantum mechanics is a universal theory so we can use a wavefunction to describe the eye. But the combined wavefunction evolves continuously, according to the Schrödinger equation and such a wavefunction...

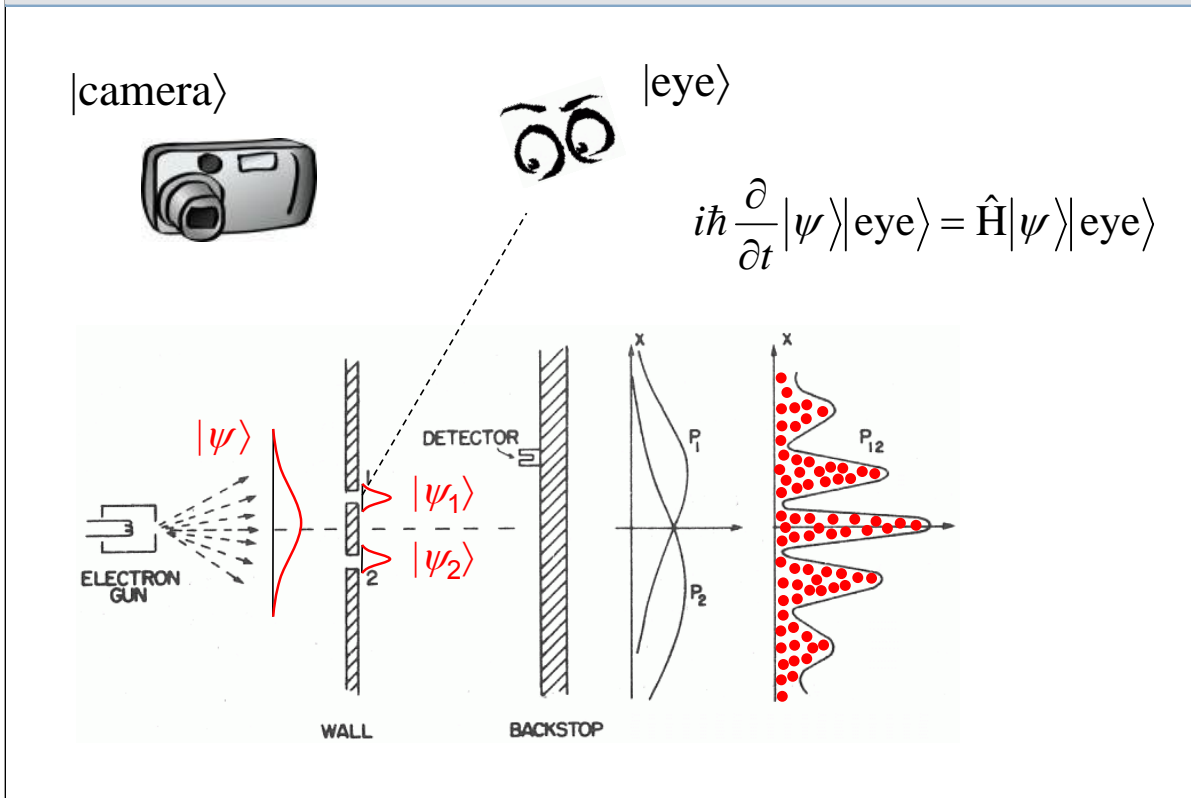
## The measurement problem (6)



... cannot collapse.

So we have a big problem: What does count as a measurement? When exactly the wavefunction collapses between the initial interaction with the electron and our perception of the electron?

## The measurement problem (7)



Can an instrument, such as this camera, perform a measurement? Or does it require a conscious observer? Perhaps with a PhD in physics?

Before I answer these questions – and they can be answered – let us look at another problem.



It is hard to believe that the existence of parallel universes is given a serious consideration in a fundamental physical theory. But many cosmologists are compelled to accept them as the quantum reality.

According to quantum mechanics, due to various interactions the wavefunction of the Universe never stays in one state but endlessly splits into more and more branches. Normally this multiplication of branches is kept in check by an external observer performing measurements and collapsing unreal branches, but now  $\psi$  contains everything that exists, including the observers. So if  $\psi$  contains everyone who is the external observer to get rid of the parallel branches?

I suspect some of you may have an answer...

## Einstein on the nature of reality



*I want to know God's thoughts; the rest are details.*

*God does not play dice with the universe .*

*God is subtle but he is not malicious.*

*Did God had any choice in the creation of the world?*

Einstein often referred to God. However, Einstein's god wasn't the personal god of mainstream religions; Einstein identified God with Nature.

When you read these remarks the message is clear: there must be reality we can understand. The problem then was – and still is today – that this reality seems to be random. Einstein could not accept it; he insisted that “God does not play dice”.

## Can we grasp quantum reality?

The image is a composite graphic. On the left, a black and white photograph of Niels Bohr and Albert Einstein is overlaid with two large speech bubbles. The bubble on the left contains the text: "What is complementary to the notion of truth? Answer: clarity." The bubble on the right contains the text: "The more success the quantum theory has, the sillier it looks." On the right side of the composite is the cover of the book "Speakable and Unspeakable in Quantum Mechanics" by J. S. Bell. The cover is dark blue with yellow text. It includes the author's name "J. S. BELL", the title "Speakable and Unspeakable in Quantum Mechanics", "SECOND EDITION", and "With a new Introduction by Alain Aspect". The Cambridge University Press logo is at the bottom.

For years Niels Bohr and Albert Einstein were trying to grasp quantum reality. Today we have several interpretations of quantum mechanics that address this issue but none of them is completely satisfactory.

I found my favourite interpretation when reading papers by John Bell, collected in a book under an unusual title. This title refers to the most widely used interpretation, the Copenhagen interpretation, which insists not only that it is impossible to solve Feynman's mystery but also makes quantum reality truly unspeakable. But Bell opted for a different interpretation.

## Pilot-wave interpretation

“The impossible has been done”<sup>1</sup>



David Bohm



Louis de Broglie

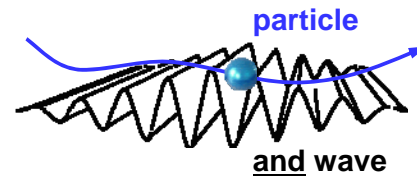
wavefunction  $\psi = R e^{iS/\hbar}$

quantum potential  $Q = -\frac{\hbar^2}{2m} \frac{\nabla^2 R}{R}$

force  $\vec{F} = -\vec{\nabla}(V + Q)$

velocity  $\vec{v} = \frac{\vec{\nabla}S}{m}$

classical      quantum



<sup>1</sup> John Bell, *Foundations of Physics* **12** 989–99 (1982)

The pilot-wave interpretation originates with Louis de Broglie. Later, David Bohm put it on firm mathematical foundations.

The formal side of this interpretation is quite simple. It starts from the Schrödinger equation and the wavefunction is written as the amplitude times the phase factor.

Next, quantum potential is introduced as the function of the amplitude.

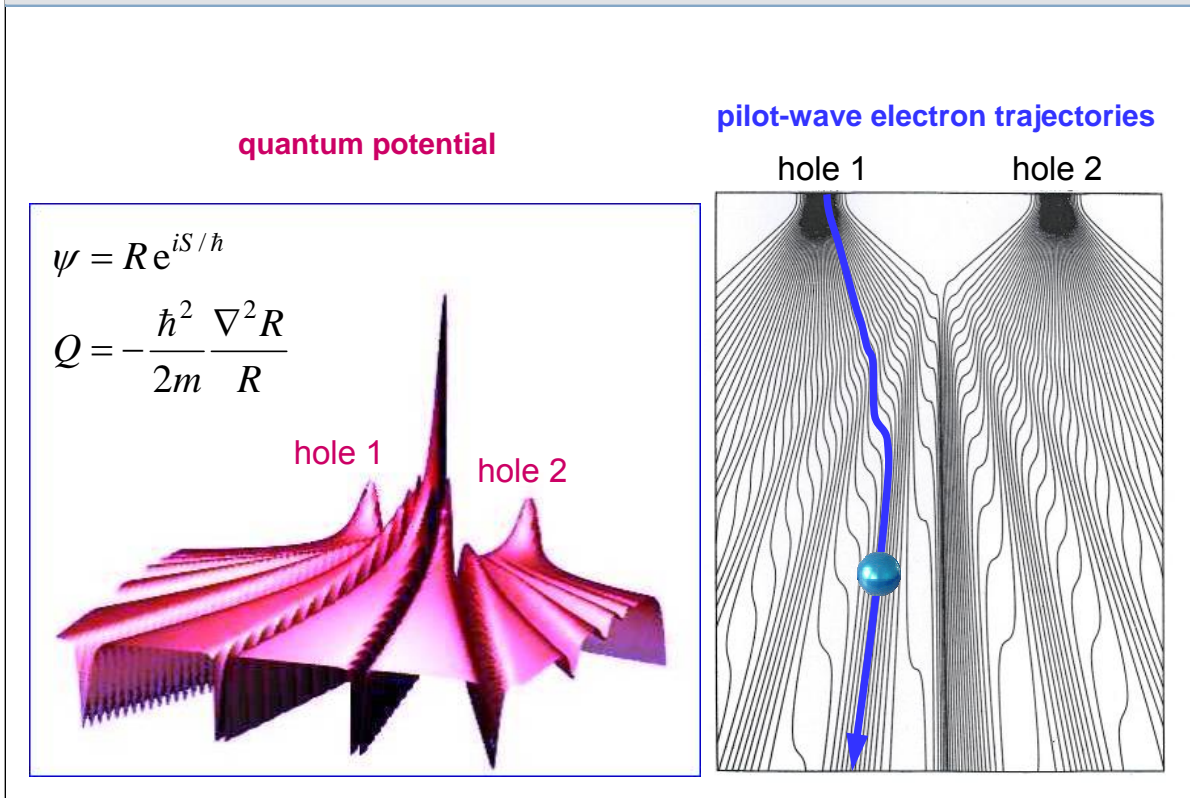
It turns out that all quantum mechanics is contained in the quantum potential. If  $Q = 0$ , we have purely classical mechanics.

This allowed Bohm to keep the velocity of a particle determined at all times.

The particle-wave dualism has been resolved: in reality both exist the particle and the wave. The wave pilots the particle along a deterministic trajectory.

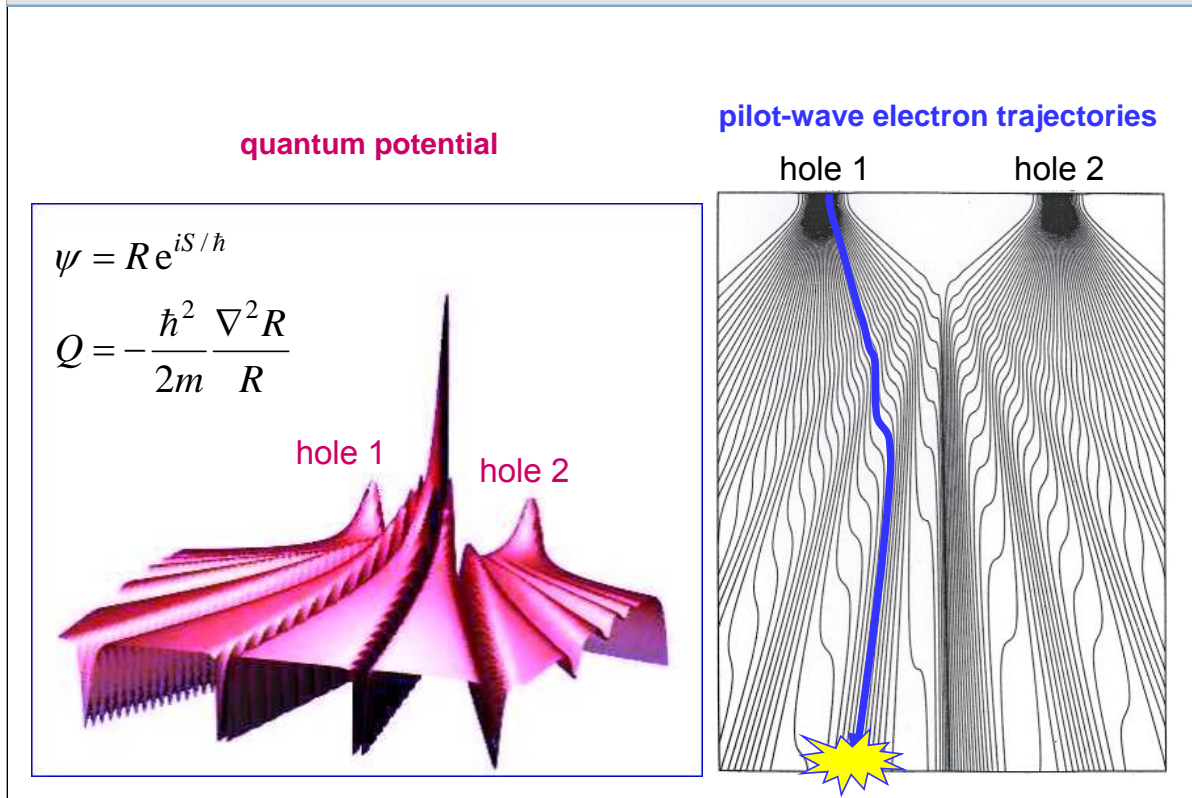
Experimentally we cannot distinguish between the pilot-wave interpretation and the Copenhagen one, because both are based on the Schrödinger equation, but conceptually “the impossible has been done”: randomness has been removed from quantum reality and God needs no dice as Einstein requested.

## An explanation of Feynman's mystery (1)



Introducing determinism into quantum mechanics allows us to understand Feynman's mystery. The wavefunction passes through the two holes and produces an interference pattern on the quantum potential. The valleys and ridges of this potential guide the electron along a well-defined trajectory. Unfortunately, we cannot know in advance which trajectory the electron follows because each time we measure its position, the act of measurement disturbs the trajectories. For example, if we block one of the holes, the interference pattern disappears and the electrons are spread smoothly on the screen. The quantum reality is still hidden from us behind the Heisenberg uncertainty principle – at least as far as the future is concerned.

## An explanation of Feynman's mystery (2)



However, when we register the electron, we can trace its trajectory back in time and say from which slit the electron has come.

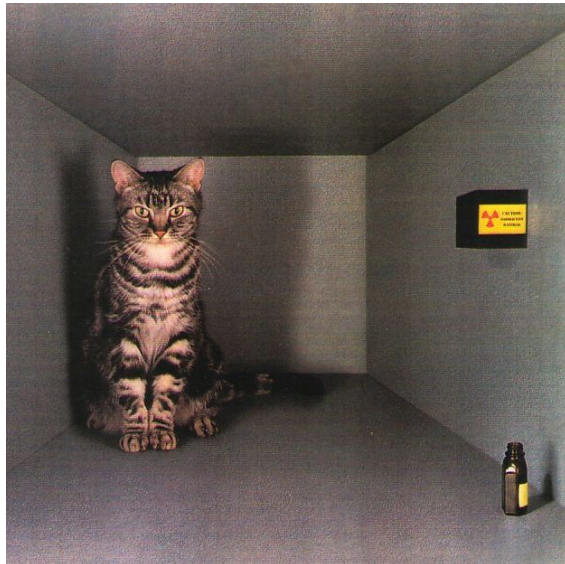
So, in fact, we can understand what Feynman couldn't.

## Saving Schrödinger's cat (1)



The pilot wave interpretation removes most paradoxes from quantum mechanics. Let us consider Schrödinger's cat. The unfortunate animal is locked in a box with a radioactive source and a mechanism, which after detecting a radioactive decay spills poison from a flask. But an atom may or may not decay, the mechanism may or may not spill the poison and the cat may or may not die.

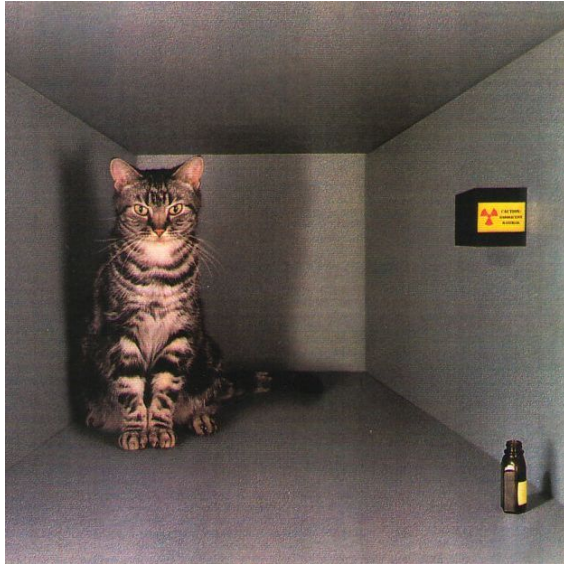
## Saving Schrödinger's cat (2)



$$|\text{cat}\rangle = \frac{1}{\sqrt{2}} (|\text{alive}\rangle + |\text{dead}\rangle)$$

This sounds straightforward but we can use a wavefunction to describe the cat. Moreover, if the whole system is well insulated in the box it will evolve into a superposition of states where the cat is dead and alive at the same time. The puzzle is how to understand this superposition.

## Saving Schrödinger's cat



$$|\text{cat}\rangle = \frac{1}{\sqrt{2}} (|\text{alive}\rangle + |\text{dead}\rangle)$$

No one has seen half-dead, half-alive cats. The pilot-wave explanation is quite simple. It is true that the feline wavefunction splits into two branches, one with the cat dead and one with the cat alive. But we have also the feline particles, that is all the atoms, nuclei and electrons the cat is made of, and these particles follow only one of the options.

This explanation solves also the measurement problem. The wavefunction never collapses. When we open the box, we don't see the feline wavefunction (remember: it is not an observable!) – we see only the feline particles. Everyday reality is given by the particles, not the wavefunctions. Nevertheless, the wavefunction pilots the particles to their destiny.



The branching of the wavefunction applies also to the whole Universe. From the Big Bang to the present day various quantum effects split the Universe into countless branches. For example, on one of them the Earth did not form, on another the dinosaurs developed intelligence, and yet on another one – probably somewhere nearby – someone else is standing in front of you now and giving this lecture. But only one of these universes is real: the Universe where we find the particles. I find this model very clear.

## Demonstration (1)



Finally, I have a demonstration.

My favourite comedian is going to make a point. The point is that you don't need to be a scientist to build models. Model building is an everyday experience.

This is a mask of Charlie's face. But the mask is back to front and if I want to touch the nose I have to reach inside the mask. However you see an illusion of a normal face here. (Those of you who sit in the first rows and have the advantage of stereo vision may need to close one eye to see this illusion better.)

The illusion occurs because whenever your eyes see patches of light resembling a face, your brain constructs a model of the face. But the modelled face is always normal, convex. Your brain is quite unable to construct a model of a face which is inside out.

Therefore...

## Demonstration (2)



...the Charlie's face is not here – it is over there, in your head, modelled by your brain. And you can clearly see that it cannot be here when I start to rotate the mask.

When you look at the other, normal side of the mask, the same process occurs: your brain builds a model of Charlie's face. In fact, whenever your eyes are open you keep building models of objects you see. And the scientific enterprise is no different: we build models to make sense of reality.



Thank you for your attention.

