The quantum view of the world 4

The nature of quantum mechanical particles

Modern physics for engineers

David Miller

Ontology

- "Ontology" in a dictionary is defined as something like
  - "the nature of being"
- More pragmatically
  - the ontology of something can be viewed as
    - the set of attributes it possesses

Ontology in quantum mechanics

When we start with quantum mechanics

- we use the words
  - "wave" and "particle"
    - but, without justification
      - we tend to bring along all of their classical ontology
        - presuming that ontology also applies to the quantum mechanical versions

Ontology of classical particles

Classical particles have attributes like

- charge
- mass
- position
- size
- shape
- and momentum

Ontology of classical particles

In the classical case

- for example, for a “particle” like a brick
  - we would normally assign size and shape to be
    - intrinsic attributes of the brick
  - but we would normally assign position and momentum (or velocity) to be
    - attributes of the state of the brick

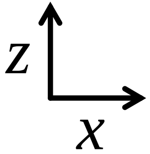
Ontology of quantum mechanical particles

Quantum mechanical “particles”
- such as an electron or a photon

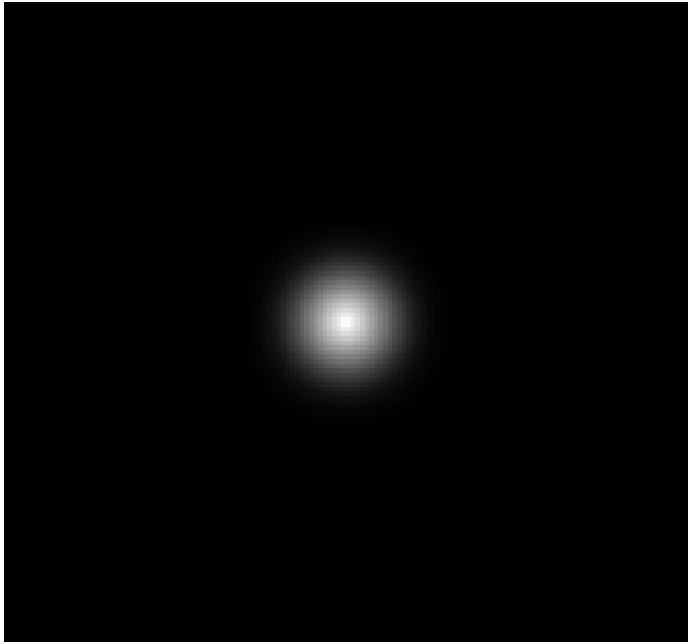
have attributes like
- charge and mass
  - both zero for the photon
- and additional attributes like spin

but we need to be much more careful with
- position, size, shape, and momentum
  - with these notions intertwined by the uncertainty principle

Hydrogen orbital probability density



x - z
cross-section
at $y = 0$

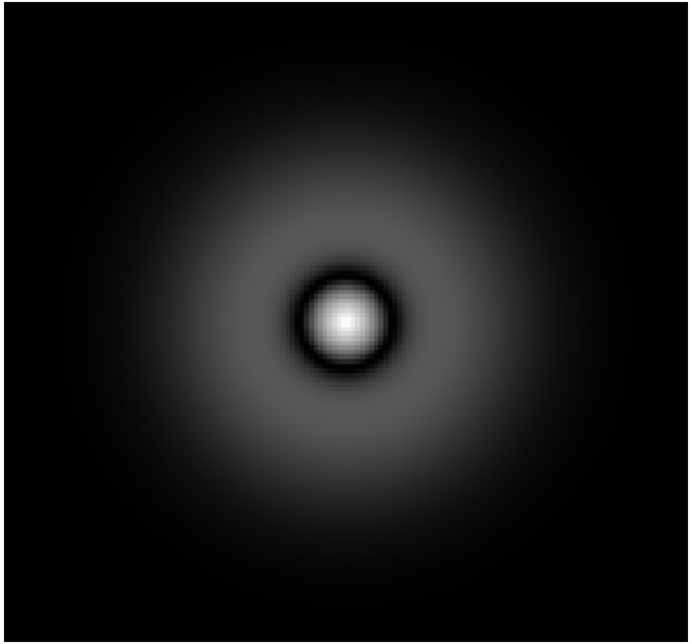


logarithmic intensity scale

1s

$n = 1$
$l = 0$
$m = 0$

Hydrogen orbital probability density



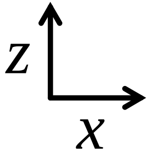
logarithmic intensity scale

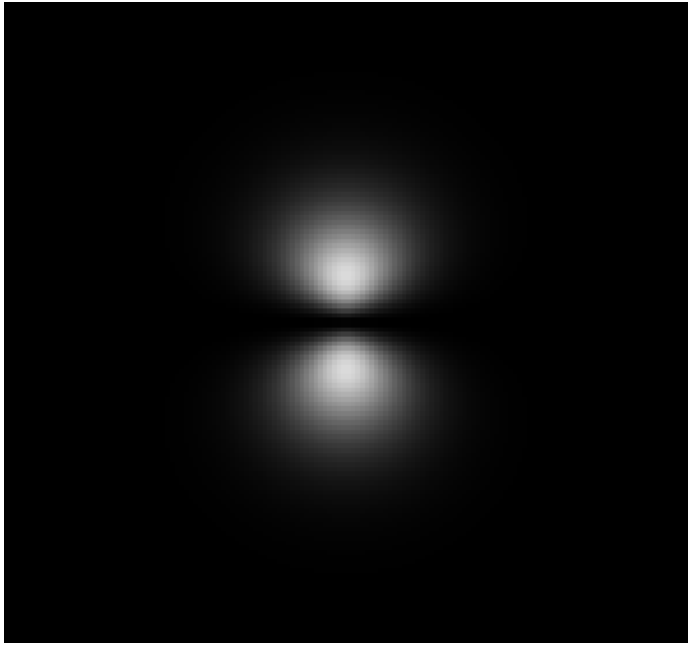
x - z
cross-section
at $y = 0$

2s

$n = 2$
$l = 0$
$m = 0$

Hydrogen orbital probability density



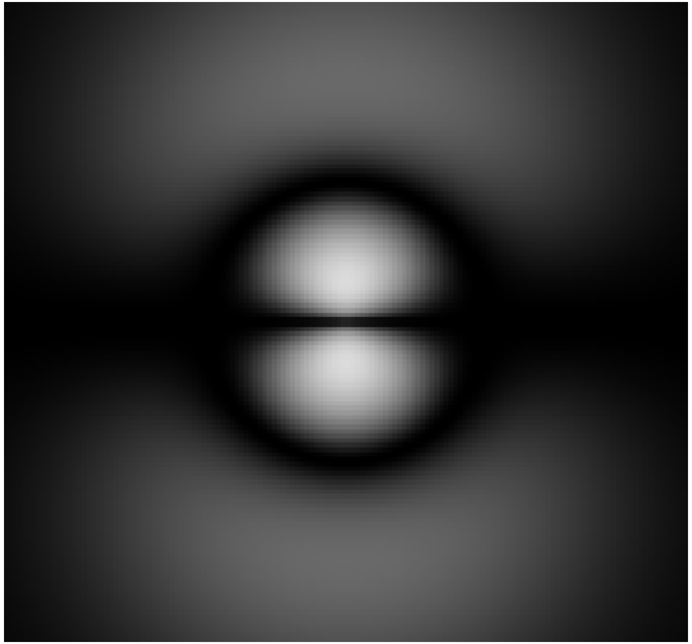


x - z
cross-section
at $y = 0$

2p

$n = 2$
$l = 1$
$m = 0$

Hydrogen orbital probability density



z x

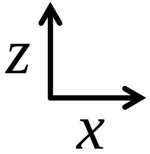
x - z cross-section at $y = 0$

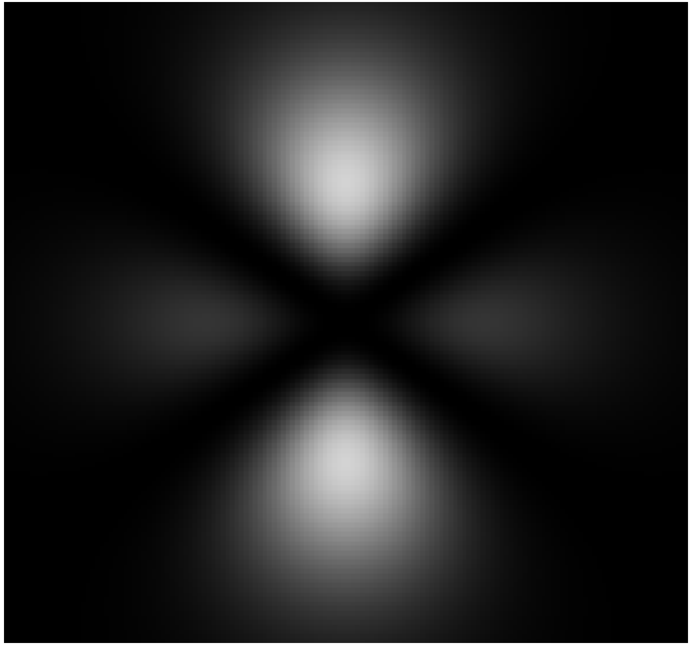
logarithmic intensity scale

3p

$n = 3$
$l = 1$
$m = 0$

Hydrogen orbital probability density



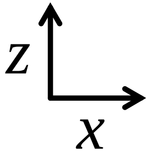


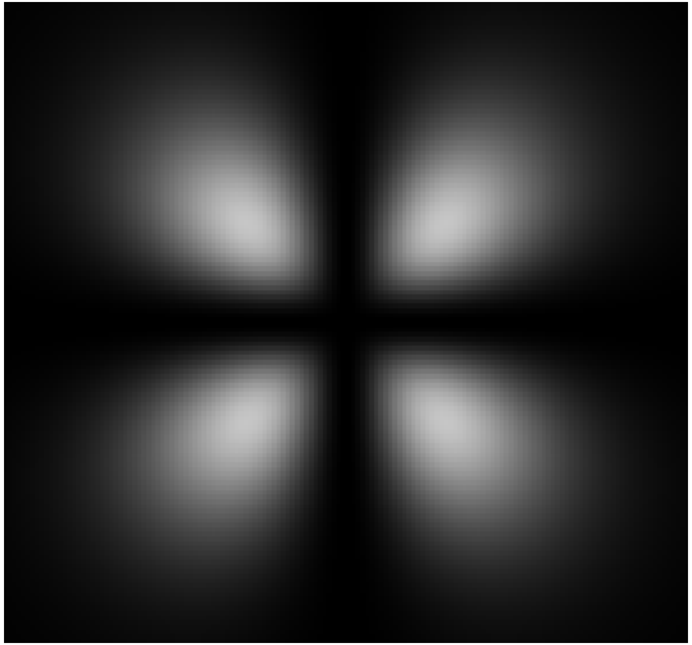
x - z
cross-section
at $y = 0$

3d

$n = 3$
$l = 2$
$m = 0$

Hydrogen orbital probability density





x - z
cross-section
at $y = 0$

3d

$n = 3$
$l = 2$
$m = 1$

Ontology of quantum mechanical particles

For a photon, we can think of

a “mode” of the electromagnetic field

such as a standing-wave mode of a resonator

or a propagating “mode” like a laser beam

as being the “state” the photon is in

or equivalently we can think that the photon occupies that mode

Ontology of quantum mechanical particles

For Young's slits

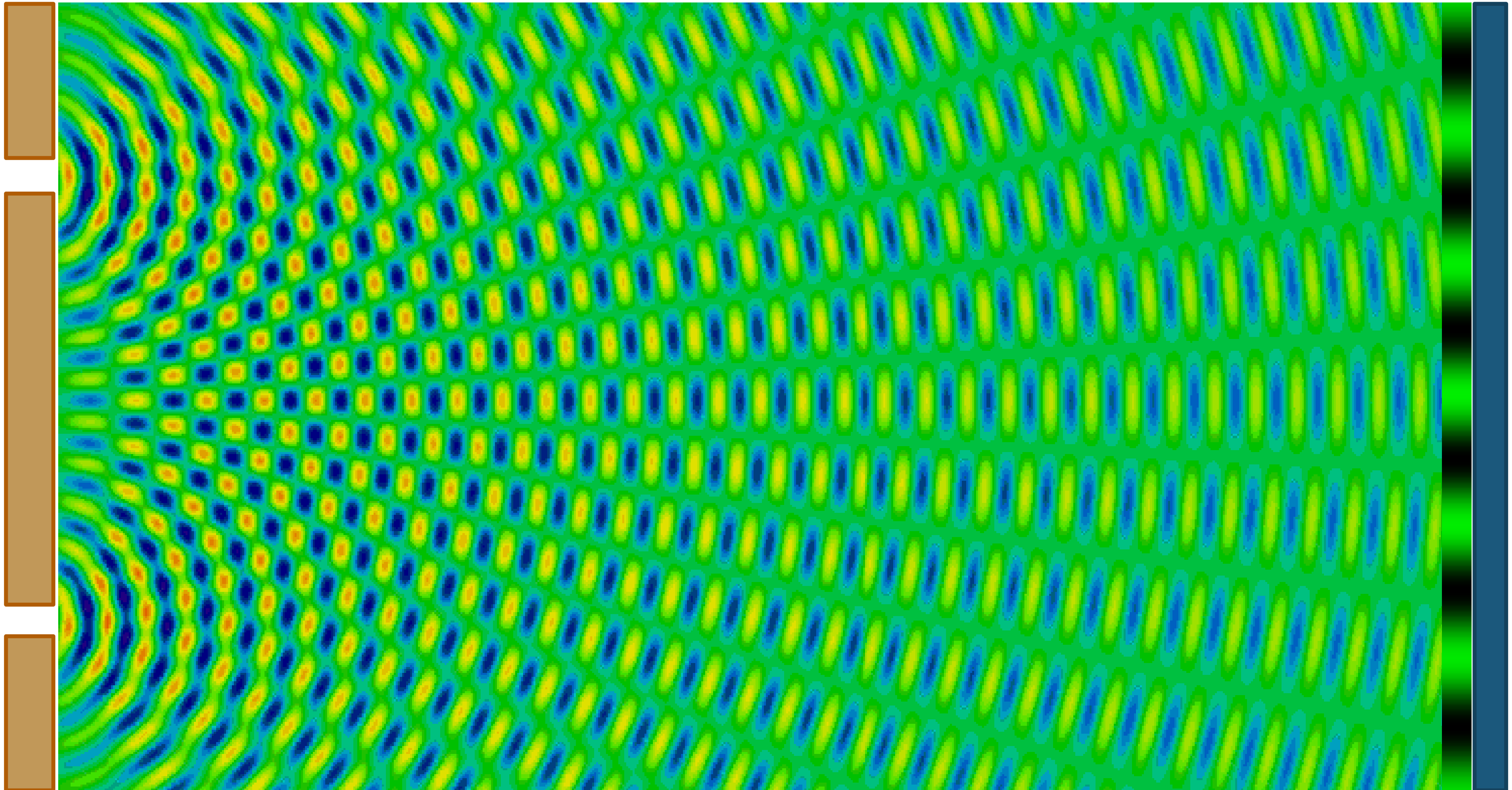
the electron or the photon

is occupying the state

corresponding to the entire diffraction pattern

Young's slits

The slits as point sources give an interference pattern



"Quarticles?"

Ontology of quantum mechanical particles

Confusion might be reduced if we

called the quantum mechanical entities by a different name

like “qwarticles”

so we could avoid bringing along all the ontology of classical particles

Ontology of quantum mechanical particles

These “qwarticles” may have attributes like

- charge, mass and spin
  - but not position, momentum, size and shape
    - Such attributes are better ascribed to the state the “qwarticle” is in
      - not to the “qwarticle” itself

Ontology of quantum mechanical particles

- An electron may be in a state
  - a particular hydrogen atom orbital, for example
- It is the orbital
  - in other words, the ***state***
  - that has attributes corresponding to
    - position, momentum, size and shape
- These are not intrinsic attributes of the electron itself

Ontology of quantum mechanical particles

- For an electron or photon in Young's slits
  - it is not meaningful to ask what slit the "qwarticle" came through
    - That is not an attribute of that "state"
      - The "state" is a wave that passes through both slits
        - and forms an interference pattern

A classical example

Ontology of computer programs

- Position is not an attribute of a computer program
  - To the extent that a computer program has a position
    - that position is an attribute of the computer that is running the program
    - not the program itself

Ontology of computer programs

- Even then the “position” is not a very definite attribute
  - It is meaningless to ask where a computer program is
    - to a precision of, say, 1 micron
- The program is a state of part of the computer memory
  - likely much larger than 1 micron
- Beyond that, it is meaningless to ask where the program is

The quantum view of the world 4

Waves and measurement

Modern physics for engineers

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Ontology of quantum mechanical waves – “Qwaves?”

Ontology of quantum mechanical waves

A more subtle point is that the "wave" here

- does not have all the attributes of a classical wave either
  - Maybe we should use another name
    - such as "qwave"

Our "qwaves" do have attributes like

- propagation
- linear superposition
- interference

Ontology of quantum mechanical waves

But, unlike classical waves

- our "qwaves"
  - may not be real, measurable entities themselves
    - and they need to correspond in some way to countable particles

Amplitudes of quantum mechanical waves

Ontology of quantum mechanical waves

Classical waves appear to be quite continuous entities

capable of any of a continuous range of amplitudes

and those amplitudes are also real, measurable quantities

with no suggestion of how they might corresponds to countable entities

Ontology of quantum mechanical waves

For quantum mechanical waves to have a direct quantitative meaning

such as leading to probability density

we should "normalize" them

so the probabilities add up to one

consistent with counting just one particle

That is not an attribute we would require of a classical wave

This normalized quantum mechanical wave

cannot take on just any amplitude

Ontology of quantum mechanical waves

This normalized quantum mechanical wave

- cannot take on just any amplitude

Also, a quantum mechanical "wave" for more particles

- does not just have a larger amplitude

Quantum mechanical waves for multiple particles are much more complex

- They can, though, describe a very rich set of possibilities
  - well beyond classical waves and
    - including the very quantum-mechanical idea of entanglement

Discussing such topics is, unfortunately, beyond what we have time for in this class

- though we will see at least how we handle working with two particles when we look at the hydrogen atom

Ontologies in quantum mechanics

Ontologies in quantum mechanics

With the revised ontologies in our "qwarticles" and "qwaves"

we can argue

there are no longer contradictions in "qwave-qwarticle" duality

The ones we thought were there in "wave-particle" duality

were because of our unjustified carrying over of classical ontologies

Quantum mechanical measurement

Quantum mechanical measurement

- When the electron or photon hits the screen
  - it makes some definite mark at a specific position
- The quantum mechanical view is that hitting the screen
  - causes a measurement of position to be made

Quantum mechanical measurement

We say that then the wavefunction "collapses" into one with a definite position

- with a probability that the electron is found at a given position
  - given by Born's rule

Born's rule says this probability is

- proportional to the modulus squared of the wavefunction at that point

“Explaining” quantum mechanical measurement?

Quantum mechanical measurement

- Note we are not explaining this measurement process or the wavefunction collapse
  - Indeed, it is quite debatable that we do not know how to do that
    - Nonetheless
      - if we take the Born rule as a pragmatic one for statistical calculation
        - we get the behavior we predict

Quantum mechanical measurement

In quantum mechanics, we can ask for a calculation

interpreted using Born's hypothesis

of something we will measure

even though we do not understand the measurement process

Generalizing Born’s postulate

Quantum mechanical measurement

We generalize Born's hypothesis formally as

> the act of measuring some quantity causes the system to collapse into an eigenstate of the quantity being measured

with probabilities given by Born's rule or a generalized version of it

Meaningless questions, and “shut up and calculate”

Quantum mechanical measurement

We regard all questions that do not correspond to something we can measure

as being meaningless

The question of which slit the electron goes through in Young's slits

is meaningless

because it is not measureable

Quantum mechanical measurement

This is known as the
  "shut up and calculate" approach in physics

It is closely related to the philosophical approach known as
  "logical positivism"

In this view, the professor responds to all dubious questions by saying
  "What was it you wanted to measure?"

The measurement problem

The measurement problem

- This measurement problem is a deep one in quantum mechanics
  - We can prove that a simple application of quantum mechanical rules
    - does not allow us to explain the "collapse of the wavefunction"
- Not only do we not know how to describe the measurement process
  - we can even prove it cannot happen!

The measurement problem

There are various proposed ways out of this difficulty

including

- the Copenhagen interpretation
- Bohm’s pilot wave
- nonlinearity in quantum mechanics
- the “many-worlds” hypothesis

No one approach is universally accepted

and none of these is easy to explain convincingly

The measurement problem

In practice we regard measurement
as something we perform
with a large measuring apparatus
on a small system
which gives results that agree
with Born's rule

In other words
"shut up and calculate"