A new introductory quantum mechanics curriculum

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IOP Institute of Physics

http://quantumphysics.iop.org

University of St Andrews

600 YEARS

http://arxiv.org/abs/1307.1484
www.compadre.org/per/perc/2013/Detail.cfm?id=5225

2013 AAPT Summer Meeting, July 13 - 17, Portland, Oregon

Why a new curriculum?

Review of approaches in the UK, IOP workshop December 2011 (led by Derek Raine)

Aims of the New QC project:

Provide freely available online material for the introductory level developing the theory using two-level systems.

- Focus on experiments that have no classical explanation, interpretive aspects of quantum mechanics and quantum information theory
- Mathematically less challenging (much of the linear algebra needed part of the resource)

The New QC Team

- Pieter Kok, Dan Browne, Mark Everitt
  Authors of ~80 short(ish) articles centred on questions.
- Antje Kohnle
  17 Interactive simulations and accompanying activities (coding by Inna Bozhinova, Aleksejs Fomins, Gytis Kulaitis, Martynas Prokopas)
- Derek Raine *(academic editor)*, Elizabeth Swinbank *(copy editor)*
- Christina Walker (IOP)
  Project management

Overview of the content (Quantum information theme)

- “Photons first”: Single photon interference via the Mach-Zehnder inferometer
- Spin ½ particle in a Stern-Gerlach apparatus
- Two-level atoms
- Two-particle states, entanglement, Bell inequality, teleportation, no cloning theorem, quantum key distribution, quantum computing
- Transition to continuous systems

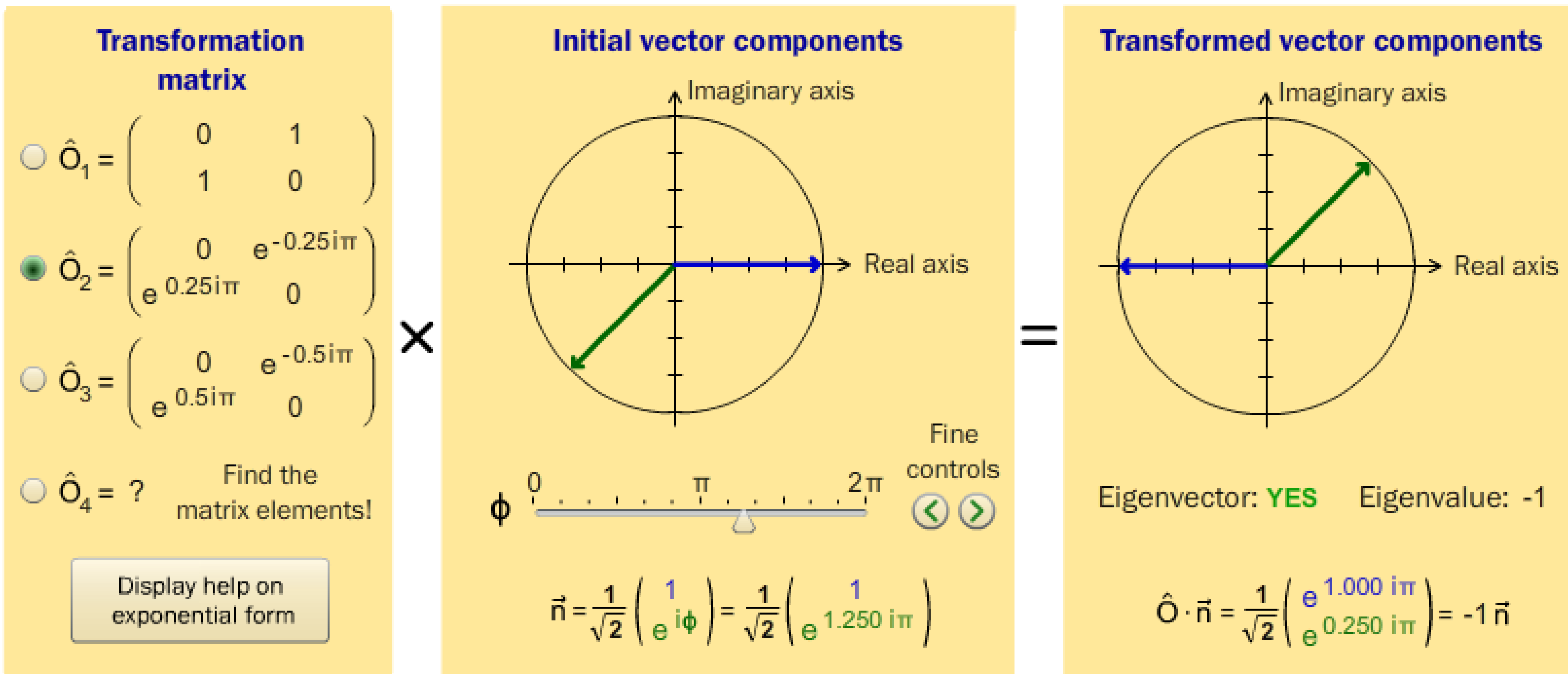
Website structure

- Five different themes (informational, foundational mathematical, physical, historical)
- Navigation panel with related content (prerequisites, further reading, glossary, exercises, sims); Users can rate difficulty, navigation panel shows all articles read with ratings.
- All content free to use, downloadable; full download and solutions available to instructors. Instructor resources (exemplars of use, forum). In future, IOP aims to provide instructors with information on student use and ratings.

Overview of the simulations

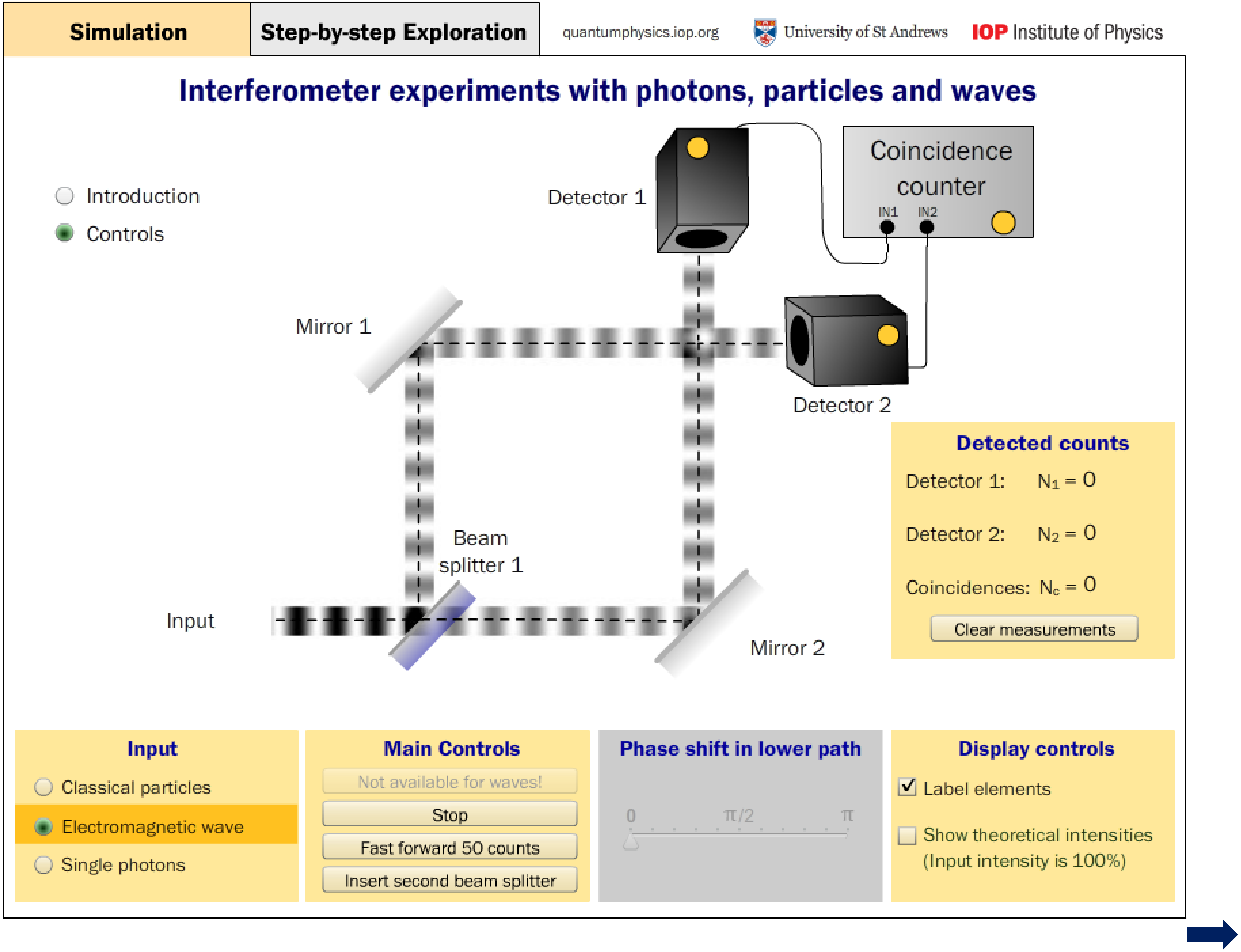
- Aims: enhance engagement, exploration, linking of multiple representations
- Make use of principles of interface design from other studies (PhET, Physlets, Clark&Mayer, etc.)
- Depict simplified, idealized situations, make the invisible visible; simple startup configuration
- Include text explanations; self-contained instructional tools
- Accompanying activities aim to promote guided exploration and sense-making; solutions available to instructors
- Topics: Linear algebra, fundamental physics concepts, single photon interference, Bloch sphere, entanglement, hidden variables, quantum information.

Graphical representation of complex eigenvectors



The graphs show the components (component 1 in blue, component 2 in green) of a two-dimensional complex unit vector $\vec{n}$ in the complex plane and the components of the transformed vector $\hat{O}\vec{n}$, where $\hat{O}$ is a 2×2 complex matrix that transforms the unit vector into a new vector in the complex plane. The first component of the vector is taken (as is often the convention in quantum mechanics) to be real and positive, and here of magnitude $1/\sqrt{2}$. The second component however is complex.

Use the slider for the angle ϕ to change the direction of the second component of the vector $\vec{n}$ in the complex plane, and the buttons to choose different transformation matrices. Complex numbers are displayed in the exponential form ($re^{i\theta}$) with modulus r and argument θ. In quantum mechanics, such a transformation matrix would represent an operator, and the vector would represent a quantum state. Note that the radius of the circle is $1/\sqrt{2}$.



Simulation
Step-by-step Exploration
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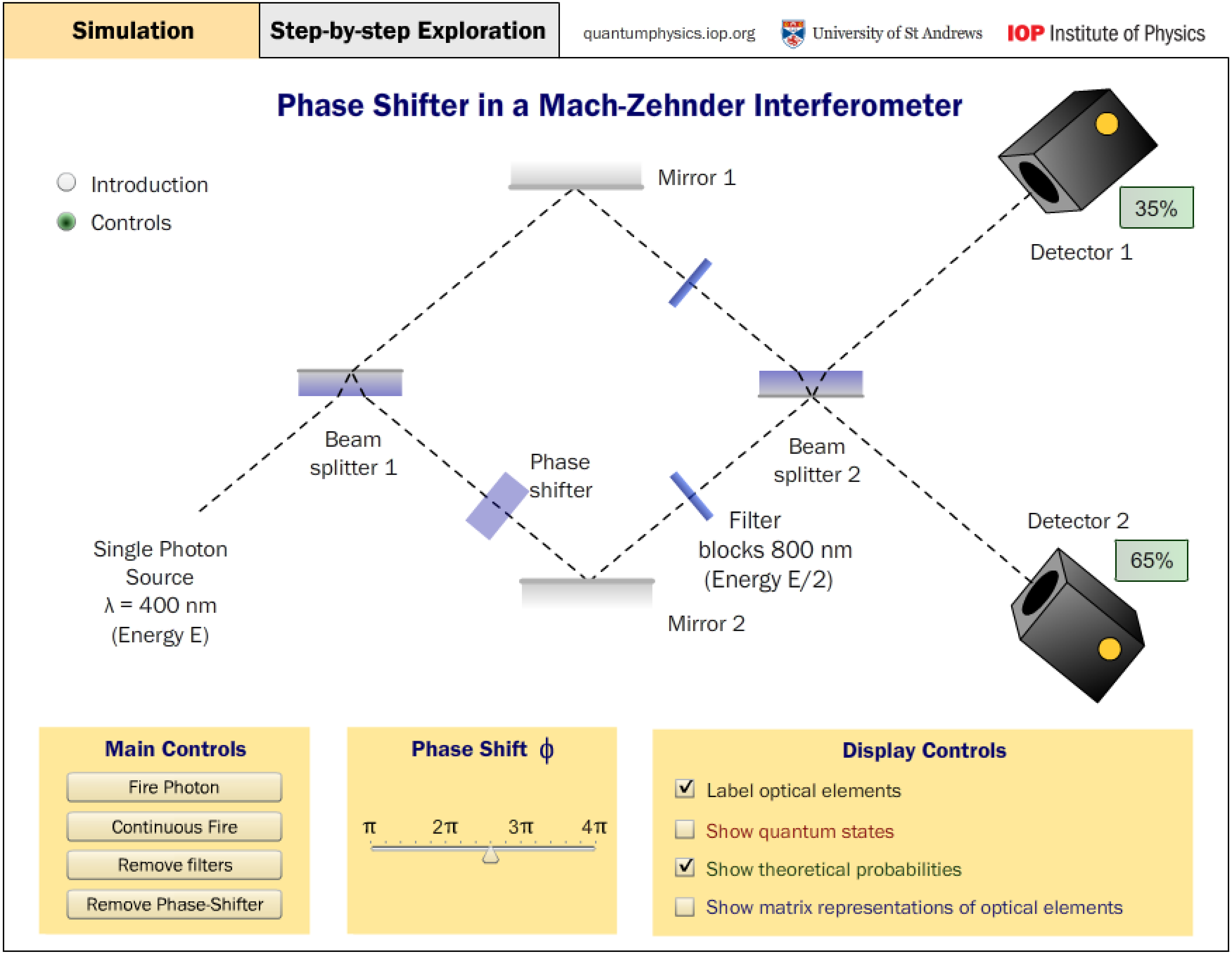
Interferometer experiments with photons, particles and waves
Introduction
Controls
Detector 1
Coincidence counter
IN1
IN2
Mirror 1
Detector 2
Beam splitter 1
Input
Mirror 2
Detected counts
Detector 1: $N_1 = 0$
Detector 2: $N_2 = 0$
Coincidences: $N_c = 0$
Clear measurements
Input
Classical particles
Electromagnetic wave
Single photons
Main Controls
Not available for waves!
Stop
Fast forward 50 counts
Insert second beam splitter
Phase shift in lower path
0
π/2
π
Display controls
Label elements
Show theoretical intensities (Input intensity is 100%)


Simulation
Step-by-step Exploration
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Phase Shifter in a Mach-Zehnder Interferometer
Introduction
Controls
Mirror 1
35%
Detector 1
Beam splitter 1
Phase shifter
Beam splitter 2
Filter blocks 800 nm (Energy E/2)
Detector 2
65%
Single Photon Source λ = 400 nm (Energy E)
Mirror 2
Main Controls
Fire Photon
Continuous Fire
Remove filters
Remove Phase-Shifter
Phase Shift ϕ
π
2π
3π
4π
Display Controls
Label optical elements
Show quantum states
Show theoretical probabilities
Show matrix representations of optical elements

Simulation | **Step-by-step Exploration**

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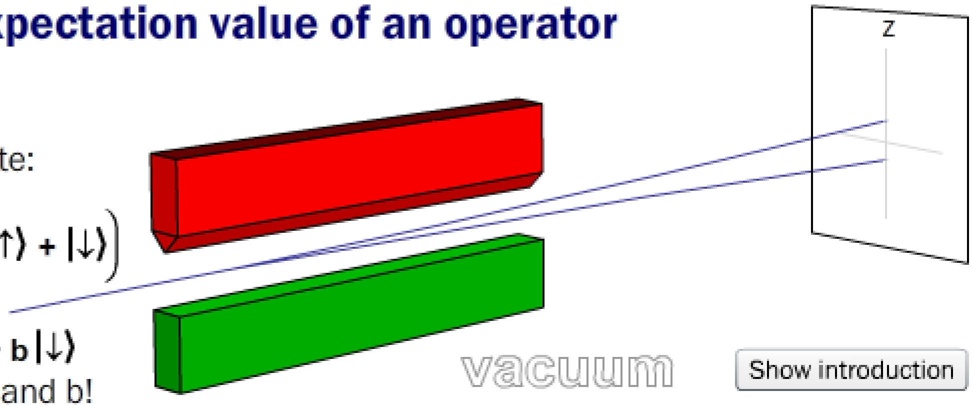
The expectation value of an operator

Input state:

- (selected) $\frac{1}{\sqrt{5}}\left(2\,|\uparrow\rangle + |\downarrow\rangle\right)$
- $a\,|\uparrow\rangle + b\,|\downarrow\rangle$ Find a and b!



Show introduction

Number of measurements

Total measurements: N_{tot} = 54

Outcome $S_z = +\frac{\hbar}{2}$: N_+ = 42

Outcome $S_z = -\frac{\hbar}{2}$: N_- = 12

Clear measurements

Main controls

Send spin 1/2 particles through the Stern-Gerlach apparatus

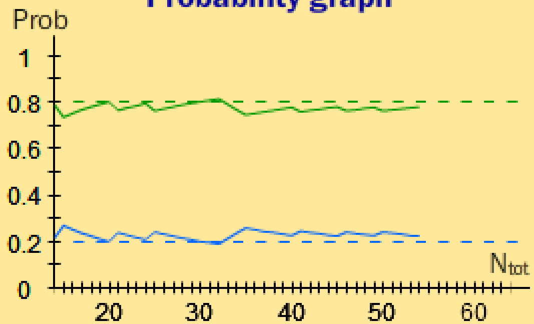
Take more measurements

Single particle

Continuous stream of particles

Fast forward 50 particles

Probability graph



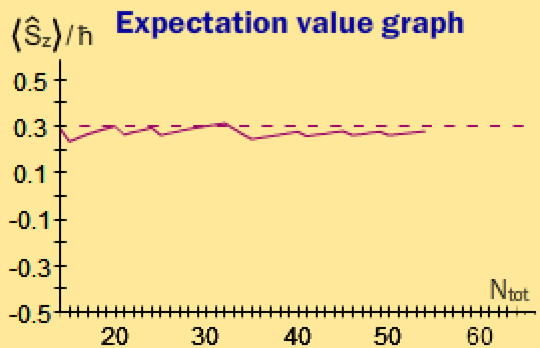
Probabilities

	Observed	Theoretical
$S_z = +\frac{\hbar}{2}$:	$\text{Prob}_+ = \frac{N_+}{N_{tot}} = 0.778$	0.8
$S_z = -\frac{\hbar}{2}$:	$\text{Prob}_- = \frac{N_-}{N_{tot}} = 0.222$	0.2

Display controls

- [x] Show probabilities
- [x] Show probability graph
- [x] Show expectation value
- [x] Show expectation value graph

Expectation value graph



Expectation value

Mean of measurement outcomes	Theoretical
$\langle \hat{S}_z \rangle = (+\frac{\hbar}{2})\text{Prob}_+ + (-\frac{\hbar}{2})\text{Prob}_-$	
$\langle \hat{S}_z \rangle = 0.278\,\hbar$	$0.3\,\hbar$

Simulation | Step-by-step Exploration

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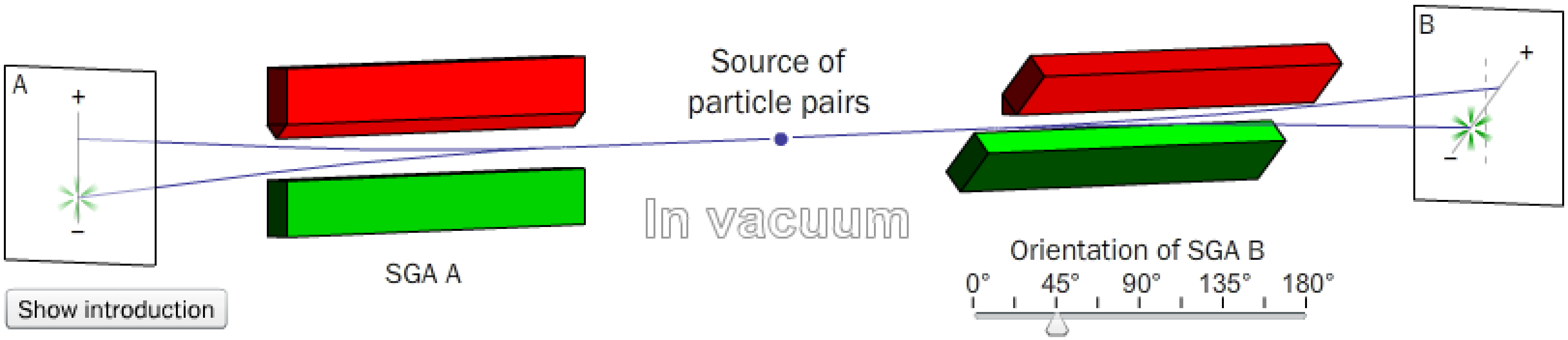
Entangled spin ½ particle pairs versus an elementary hidden variable theory



Show introduction

Main controls

- Quantum theory
- Hidden variable theory (selected)

Send pairs with pre-determined spin vectors through the SGAs.

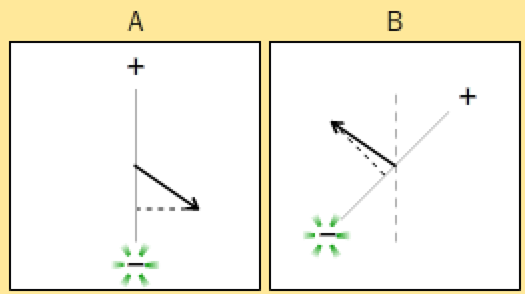
Single particle pair

Continuous stream of pairs

Fast forward 50 particle pairs

Hidden variables

Locally pre-determined opposite spin vectors



Paired Measurements

N_{total} = 156 | Probabilities | Quantum prediction

Outcome Same (A,B) = (+,+) or (−,−):

N_{same} = 40 | $P_{same} = \frac{N_{same}}{N_{total}} = 0.256$ | 0.146

Outcome Opposite (A,B) = (+,−) or (−,+):

N_{opp} = 116 | $P_{opp} = \frac{N_{opp}}{N_{total}} = 0.744$ | 0.854

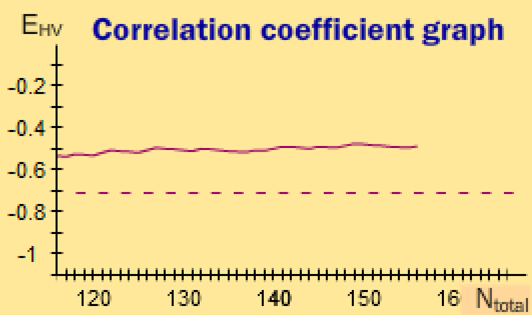
Clear measurements

Display controls

☑ Show correlation coefficient

☑ Show correlation coefficient graph

Correlation coefficient graph



Correlation coefficient

Expectation value E: average of measurement outcomes AB, where AB = +1 (same), AB = -1 (opposite)

$E_{HV}(AB) = P_{same} - P_{opp} = -0.488$

Quantum prediction: -0.708

Simulation | Step-by-step Exploration

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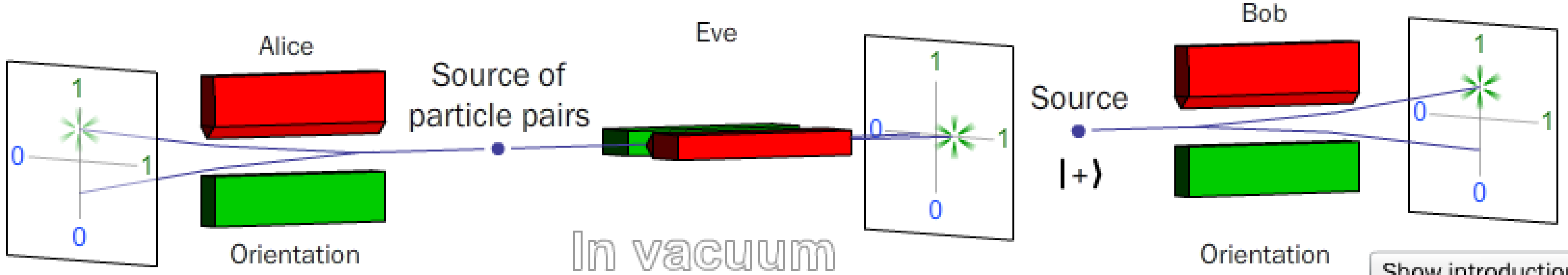
Quantum key distribution with entangled spin ½ particles



Show introduction

Orientation of SGA A: Z X — Random orientations / Fixed orientations — Orientation of SGA B: Z X

Main controls

Send entangled spin ½ particle pairs

Take more measurements

Single particle pair

Continuous stream of particle pairs

Fast forward 50 particle pairs

Let Eve intercept and resend particles

Stop eavesdropping

Alice Basis	Alice Outcome	Eve Basis	Eve Outcome	Bob Basis	Bob Outcome	Alice and Bob Same bases?	Key Bob inverts value
Z	1	X	1	Z	1	YES	ERROR
Z	1	Z	0	Z	0	YES	1
Z	0	Z	1	Z	1	YES	0
X	0	Z	1	X	0	YES	ERROR
X	1	X	0	Z	0	NO	
X	0	Z	0	X	1	YES	0
X	1	X	0	X	0	YES	1

Display controls

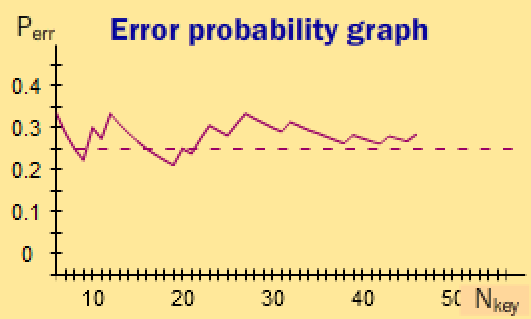
☑ Show secure key

☑ Show errors

☑ Show error probability graph

Clear measurements

Error probability graph



Errors

		Theoretical
Total pairs:	$N_{tot} = 100$	
Key bits:	$N_{key} = 46$	$0.5\,N_{tot}$
Errors:	$N_{err} = 13$	$0.25\,N_{key}$
Probability:	$P_{err} = \frac{N_{err}}{N_{key}} = 0.283$	0.25

Optimization of simulations and activities

- See PERC poster (A Kohnle, C Baily, C Hooley, B Torrance)
- 38 hours of observation sessions with 17 student volunteers in February/May 2013 from the St Andrews introductory level.
- Use of two simulations (single photon interference, hidden variables) in the Boulder modern physics course (N Finkelstein, C Baily)
- Use of three simulations (+ entanglement) in the St Andrews quantum physics course.
- Revisions to all simulations and activities where appropriate

Future activities

- Multi-institutional observation sessions and trials in introductory qm courses.
- Build a community of users (instructor resources, exemplars of use, user forum).

- Further sims (+ all as HTML5/JS touchscreen versions) and additional activities (more exploratory and collaborative in nature); revisions to articles based on user input.
- Investigate student difficulties with the New QC. Develop research-based interactive engagement materials / concept tests etc.