To demonstrate the process of weak measurement for atoms using a modified Stern-Gerlach apparatus.

Rob Flack HEP, UCL.
Basil Hiley TPRU, Birkbeck.
Jim Clarke ASTeC, Cockcroft Institute.
Kiri Marinov ASTeC, Cockcroft Institute.

See our HEP seminar in June 2012 for more details of the theory.
We were also invited to give a seminar at Akloster, Sweden.

Introduction

Aharonov, Y., Albert, D. Z. and Vaidman, L.
How the Result of a Measurement of a Component of the Spin of a Spin-1/2 Particle Can Turn Out to be 100,
Phys. Rev. Lett., 60 (1988) 1351-4.

Aharanov et al proposed the idea of 'Weak measurement" and conjectured that the measured value could lie outside the range of the observable's eigenvalues.

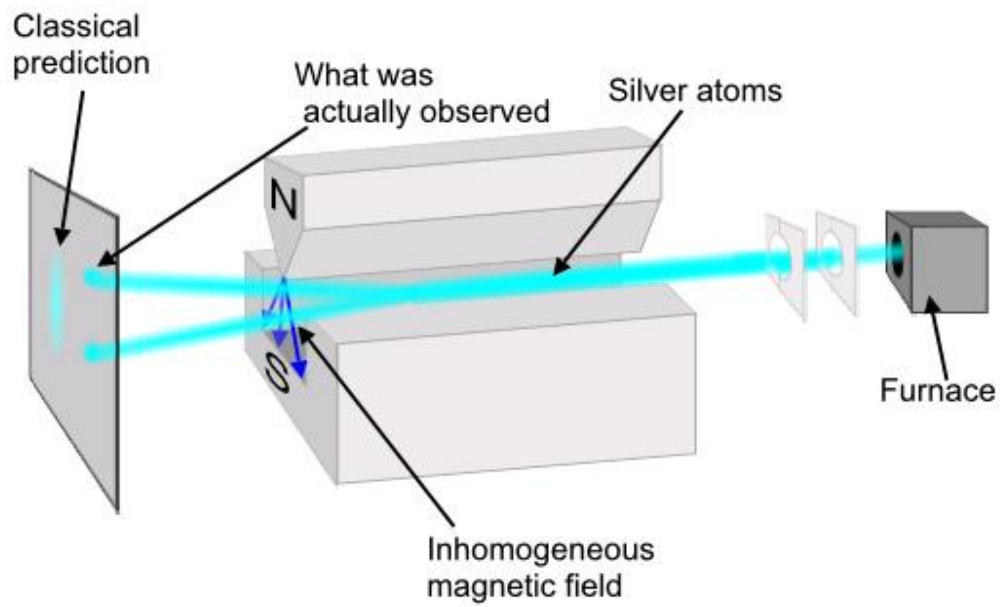
They give the example of the measurement of the component of spin could in effect be "amplified" by a factor of 100.

This "amplification" may have applications for the detection of very small signals.

Original Stern-Gerlach experiment

Silver atoms were originally used. They have one valence electron around a filled core and behaves like a spin-1/2 particle.

The classical prediction is the beam should spread out in a continuous manner.



The observation is a beam split into two parts: spin-up, spin-down.
A STRONG MEASUREMENT

Reduce the magnetic field the beams are not well separated but overlapping.
A WEAK MEASUREMENT

Von Neumann's collapse of the wave function

Inducing phase changes which has unexpected consequences

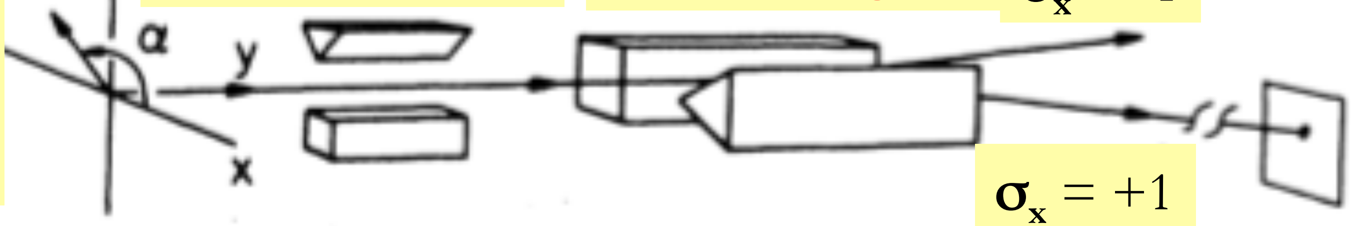
Using a modified Stern-Gerlach apparatus

I. M. Duck. P. M. Stevenson and Sudarshan, Phys. Rev. D, 1989

The particles enter along the y-axis with spin oriented at an angle α in the zx-plane.

The first S-G is oriented along the z-axis.
Weak

The second S-G is oriented along the x-axis.
Strong



$\sigma_x = -1$

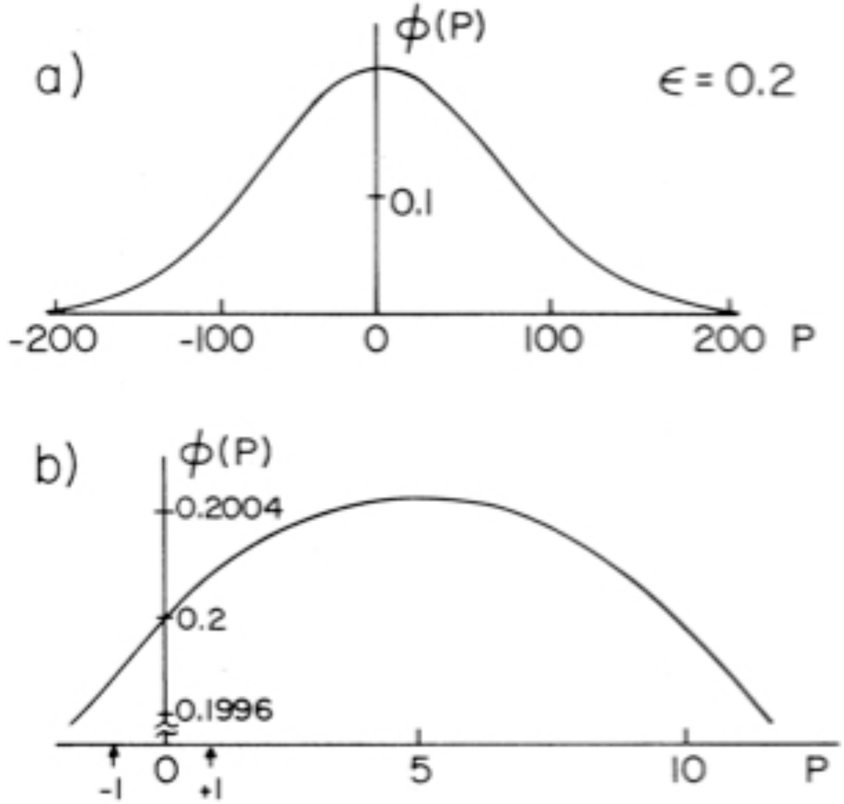
$\sigma_x = +1$

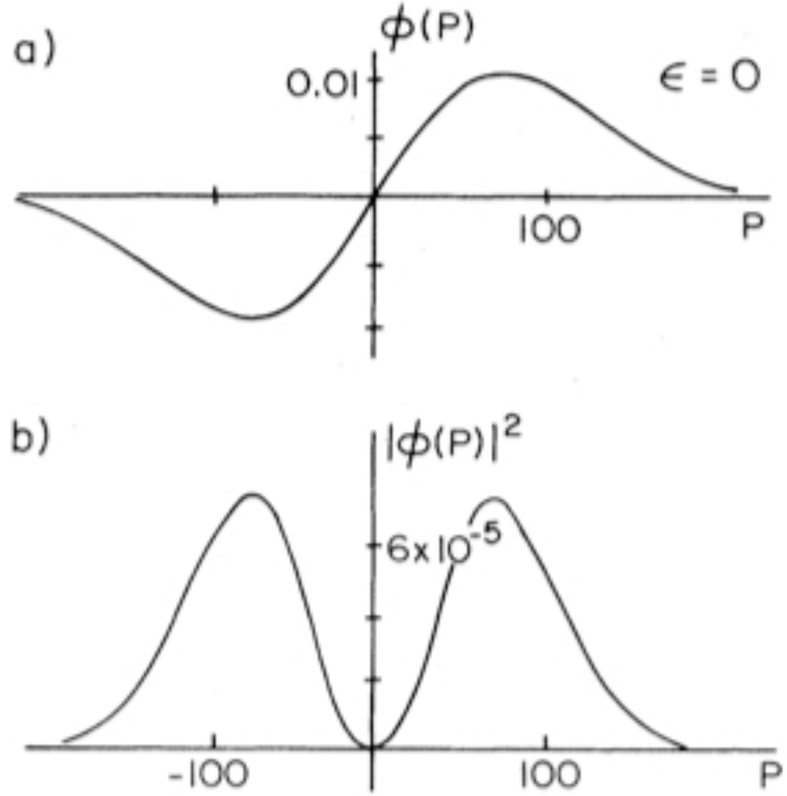
σ_x and σ_z are non-cummuting variables

$A_w = \mu\tan(\alpha/2)$, $\mu \propto$ magnetic moment of the particle.
Note what happens as α approaches π, A_w gets very large.

Propose to construct this experiment using Aluminium atoms.

What happens as α approaches π?
Let $\varepsilon = \pi - \alpha$.
Scale is $\sigma_x = 1$.





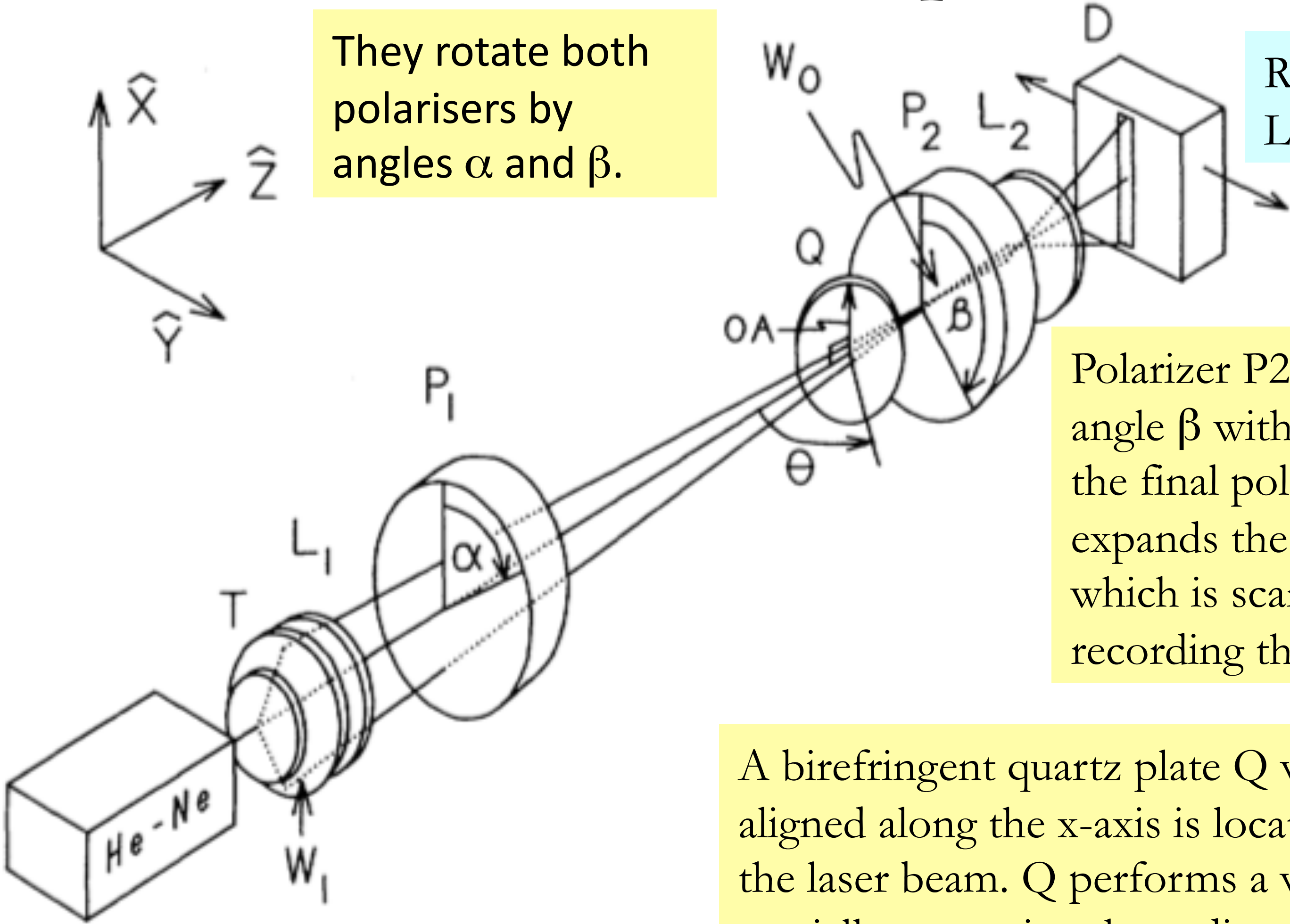
(a) $\phi(p)$ resembles a Gaussian.
(b) Close up shows the peak is at 5.

(a) $\phi(p)$ is now antisymmetric.
(b) The resulting probability distribution peaks at ±70.

Realisation of the optical analogue

They rotate both polarisers by angles α and β.

Ritchie et al. Phys. Rev. Lett., 66, 1107



Polarizer P2, whose axis makes an angle β with the x-axis, post selects the final polarization state. Lens L_2 expands the image onto a detector D which is scanned along the y-axis, recording the intensity.

A birefringent quartz plate Q with optic axis (OA) aligned along the x-axis is located near the focus of the laser beam. Q performs a weak measurement by spatially separating the ordinary and extraordinary polarization components by a distance small compared to the waist of the beam.

Frequency-stabilized He-Ne laser is collimated, focused, and polarized at an angle α relative to the x-axis by telescope T, lens L_1, and polarizer P_1.

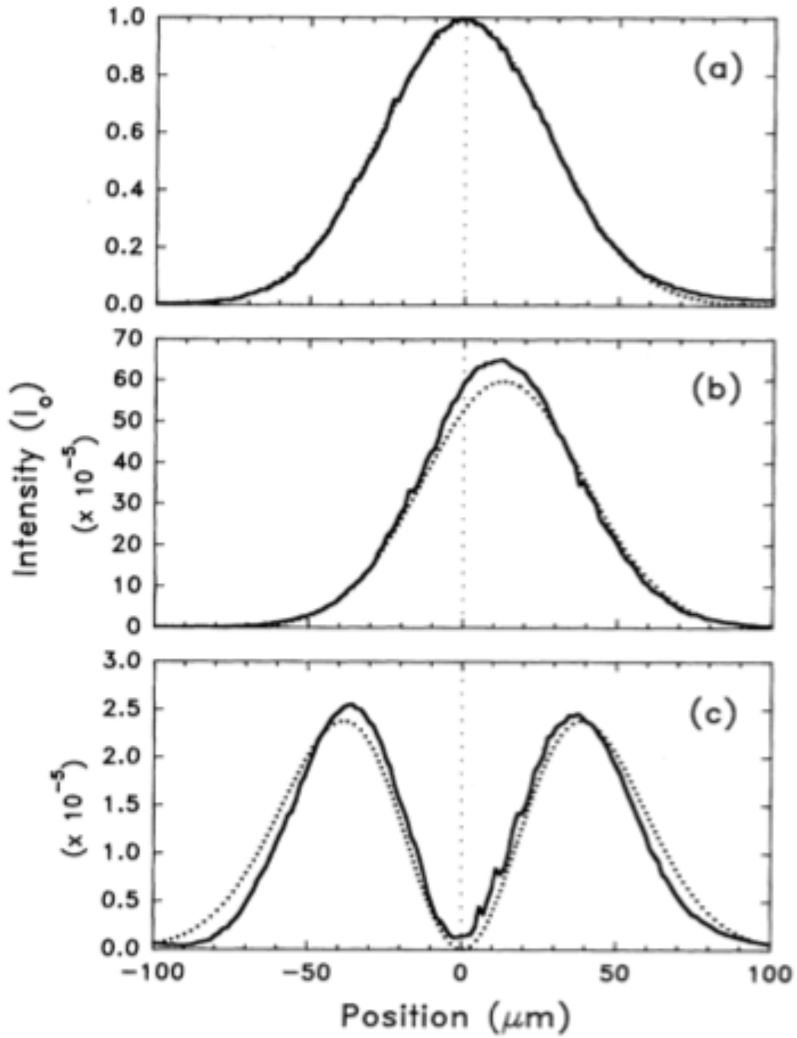
Results of the optical analogue

The wavelength of the light a=0.64μm

(a) $\alpha=\beta=\pi/4$, corresponding to aligned polarizers. The measured intensity profile is the result of the constructive addition of two approximately Gaussian distributions.

(b) $\alpha= \pi/4$, $\beta =3 \pi/4+0.022$, corresponding to a measurement of the weak value. The centroid of the distribution is shifted by A_w=l2μm=20a.

(c) a= π/4, P=3π/4, corresponding to crossed polarizers, or orthogonal initial and final states. The separation of the two peaks is 120a.



Stern-Gerlach using aluminium atoms

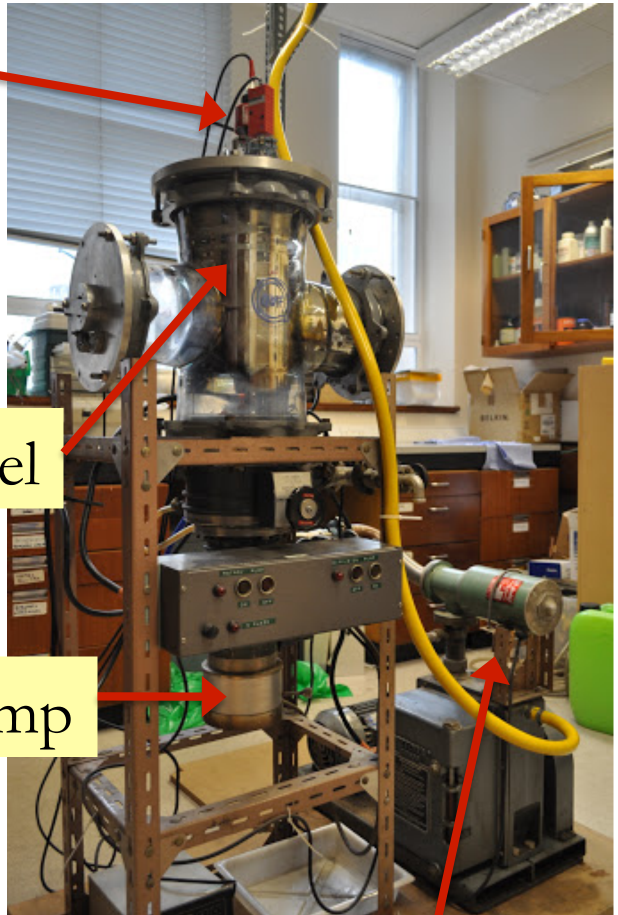
- Magnetic moment $0.78\mu_B$
- Vapourising temperature ~ 1000 K.
- Vacuum level ~ 10^{-7} Torr.
- Average speed of atoms ~1000 m/s (Maxwell-Boltzmann distribution).
- For a magnetic field intensity ~100 T/m the predicted separation of the spin-up/down beams ~4 mm.

Vacuum system and proto-oven

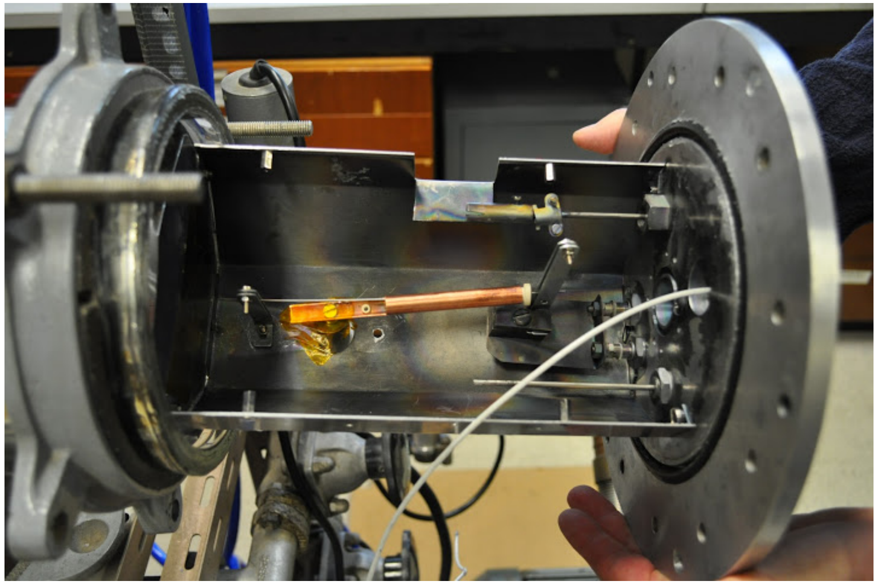
Pirani and Penning gauges

Vacuum vessel

Diffusion pump



Rotary pump



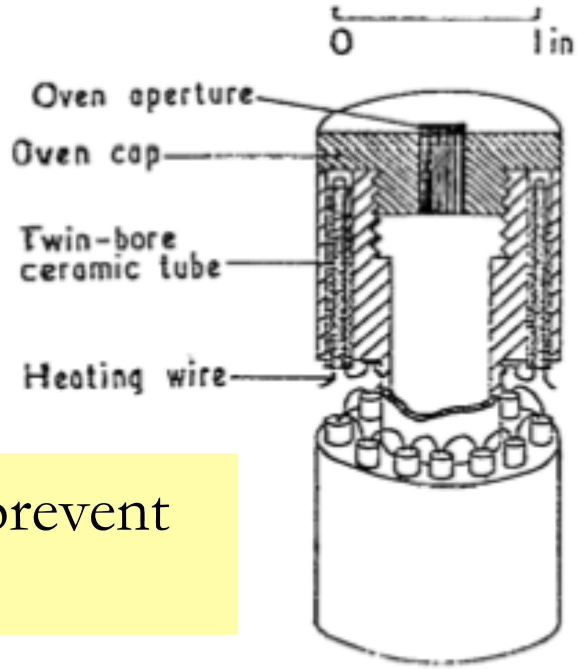
Simple proto-oven made of copper with a tungsten wire heater + ceramic insulators

Oven

I. V. Hertel and K. J. Ross, J. Sci. Instrum. 1, 1245 (1968).

Make with ceramic glass which is resistant to temperature > 1000 K

Do not want the aluminium atoms in direct contact with the heater filament as it will ionise the atoms.



Heat the aperture and collimator to prevent build up of atoms of aluminium.

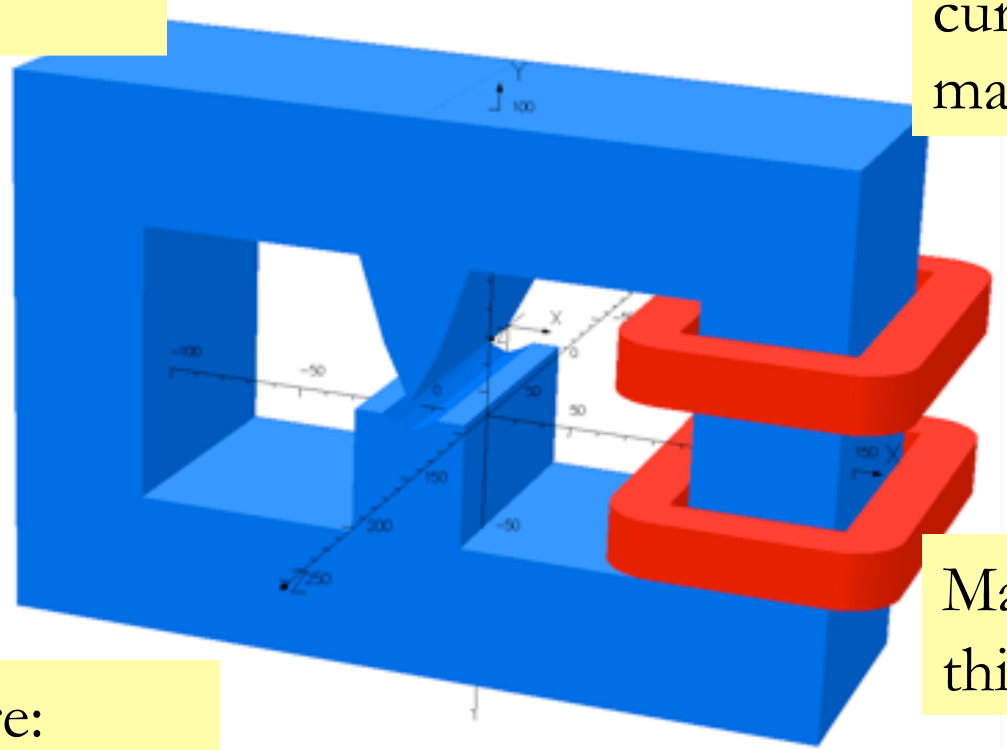
For accurate alignment the oven, collimator and beam tube will be engineered as one piece

Magnet design

Magnet designed using the OPERA software

Core is made of iron type AISI 1016 (EN 3).

Design calls for 1600 Ampere turns. If current is 5A then 4 magnets of 800 turns.



Made from 1 mm thick plates.

Dimensions are:
300 x 200 x 100 mm.

Order of construction

- Make the oven and the beam tube:
  - Obtain a steady beam of atoms along the tube
  - Measure the width of the beam
- Make one magnet for Stern-Gerlach experiment.
  - Observe and measure the separation of the two components of the spin.
  - Experiment reducing the size and strength of the magnet.
- Make the weak magnet.
  - Observe the weak separation.
- Make the strong magnet.
  - Observe the weak measurement process and the weak value.

Conclusion

- Weak measurement is a well defined quantum mechanical process.
- The modified Stern-Gerlach is a well motivated experiment.
- The vacuum vessel, pumps, gauges and proto-oven have been acquired and working perfectly.
- Collaborators at the Cockcroft have designed the magnets.
- **Remarkable progress in a short time**

Backup slides

Experiments using weak measurement

The weak and strong measurements are carried out on non-commuting variables: Spin in the z and x axes; momentum and position.

There is a debate as to whether this is really a meausrement process. I will illustrate that by looking at an experiment using a modified Stern-Gerlach where the usual spin measurement is ampilified.

Then I will look at how the particle trajectories in a Young's 2-slit experiment can be mapped out.

Particle physicists use weak measurement

G. J. Feldman et al., Phys. Rev. Lett. 48, 66 (1982)

The weak measurement is a sum of overlapping Gaussians, each one centred on one of the values of the variable being measured.

If the entire distribution of events is mapped out then its centroid is the mean value of the variable being measured.

In the measurement of the τ-lifetime the position resolution of the detectors used was not good enough to resolve the decay length of the τ-lepton in a single event.

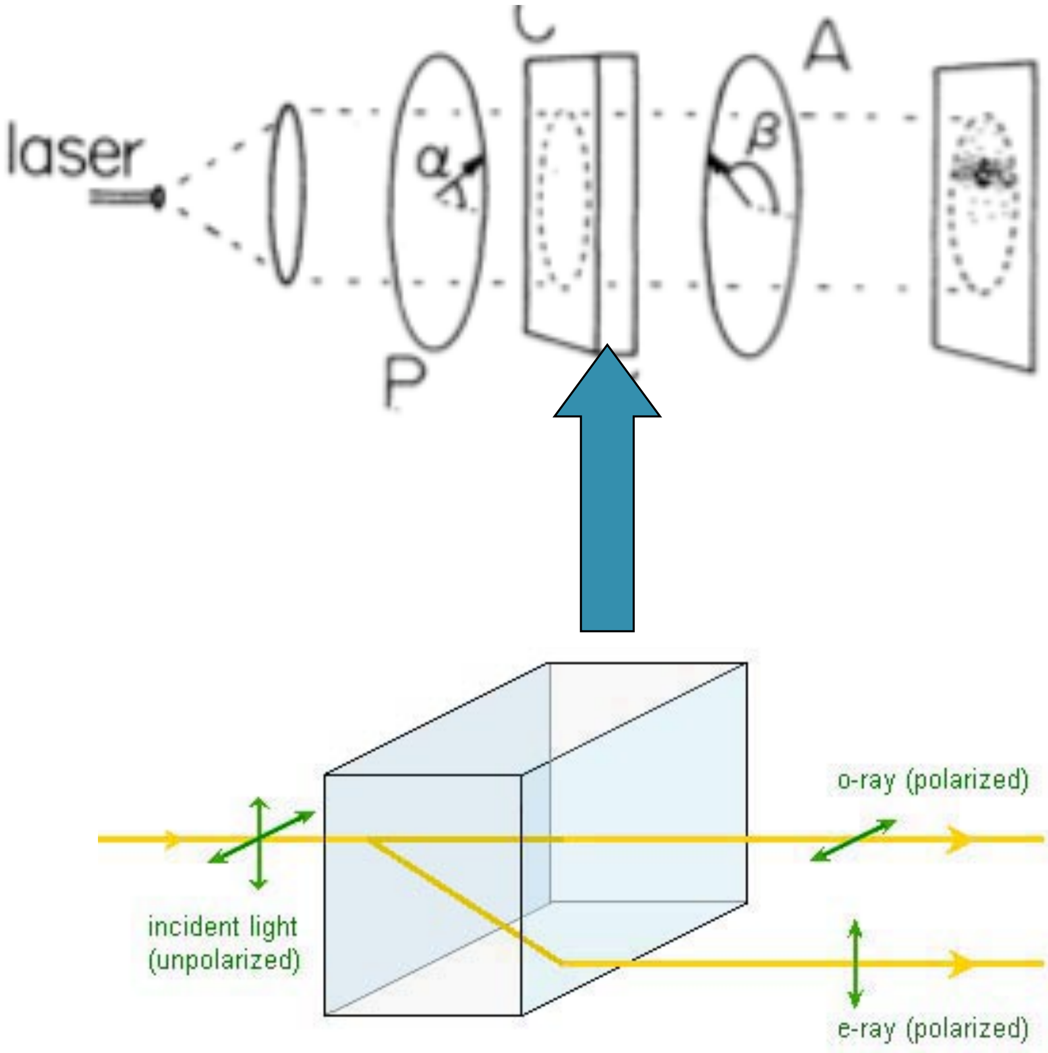
The "apparent decay length" has a very broad distribution, dominated by the position-measurement errors. With a large sample of events the life-time can be deduced from the mean (centroid) of the distribution.

Optical analogue of the Stern-Gerlach apparatus

Polarised light from a laser is used instead of spin-1/2 particles.

Polariser P and analyser A select the intial and final polarisations at angles α and βrespectively.

A birefringent crystal provides the weak measuring device. It introduces a small lateral displacement between the o-ray and the e-ray.

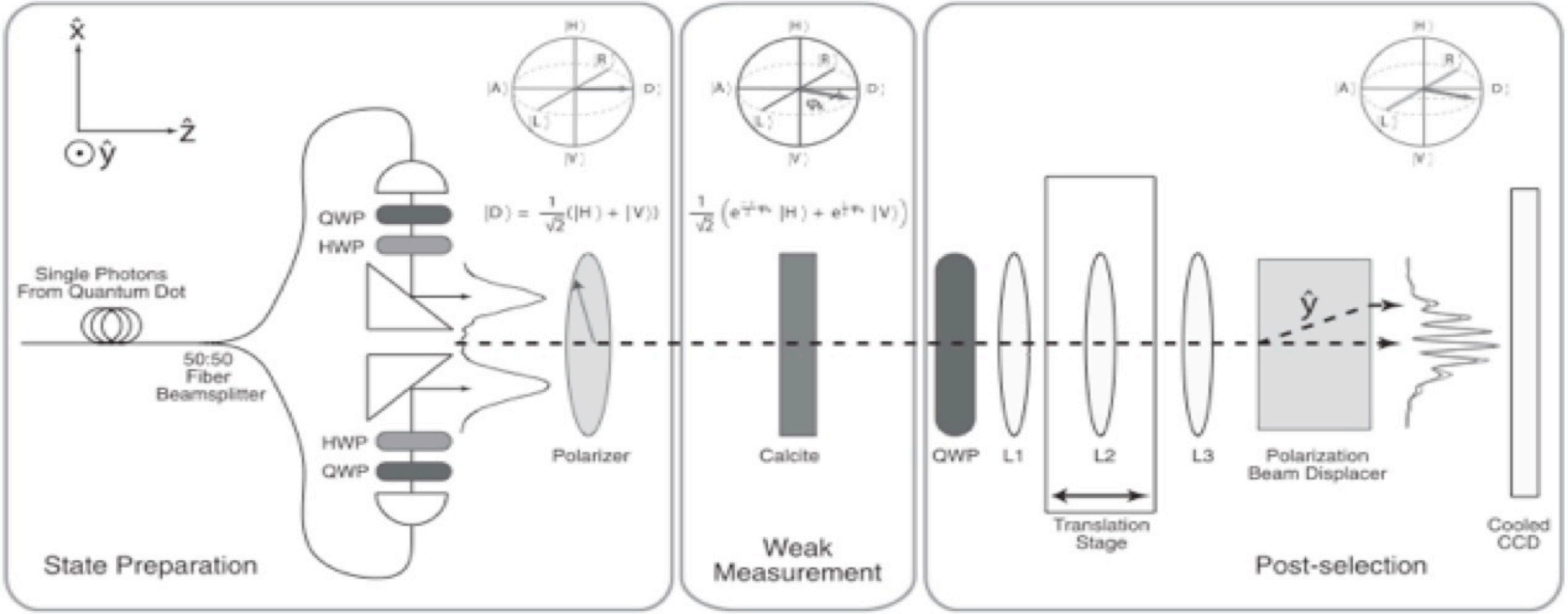


Mapping trajectories of photons in 2-slit experiment

Kocsis et al, Science 332:1170, 2011

A quantum dot was used as a source of single photons. This made sure that only one photon was in the apparatus at a time.

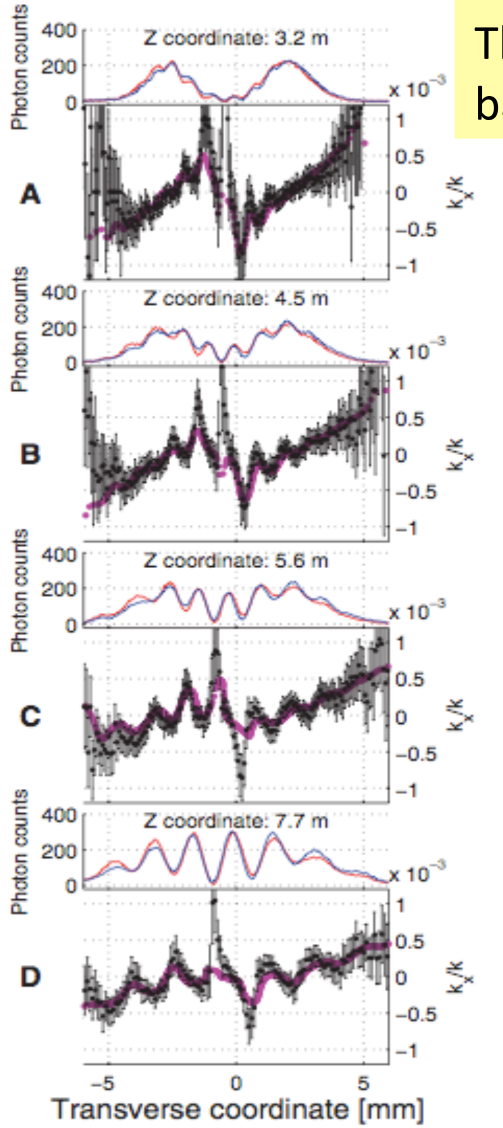
The strong measurement of position is carried out by observing the fringe pattern at a range of horizontal positions



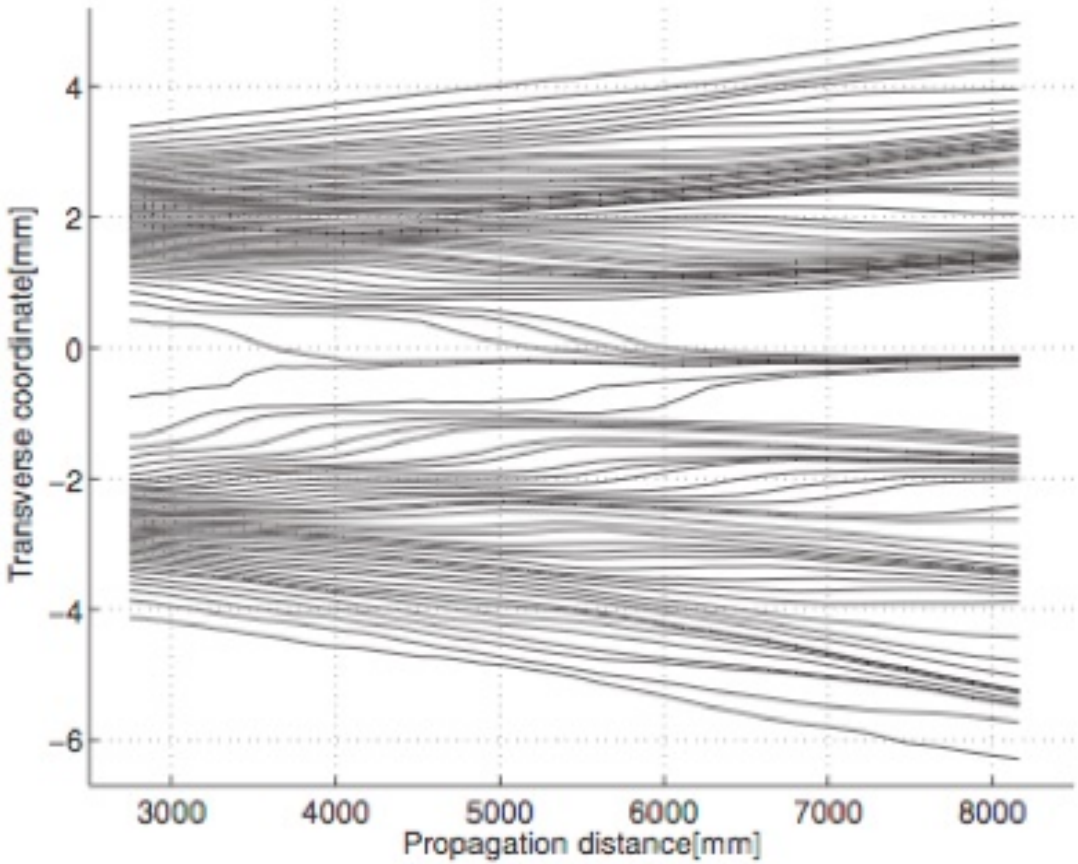
A 50:50 beam splitter.

Birefringent calcite is used to for the weak measurement of momentum. It imparts a small k_x-dependent phase shift (p=hk). Linear polarisation becomes slightly elliptical

Reconstruction of the trajectories



The majenta line is after constant background has been subtracted



Preliminary thoughts on using massive particles
(work in progress)

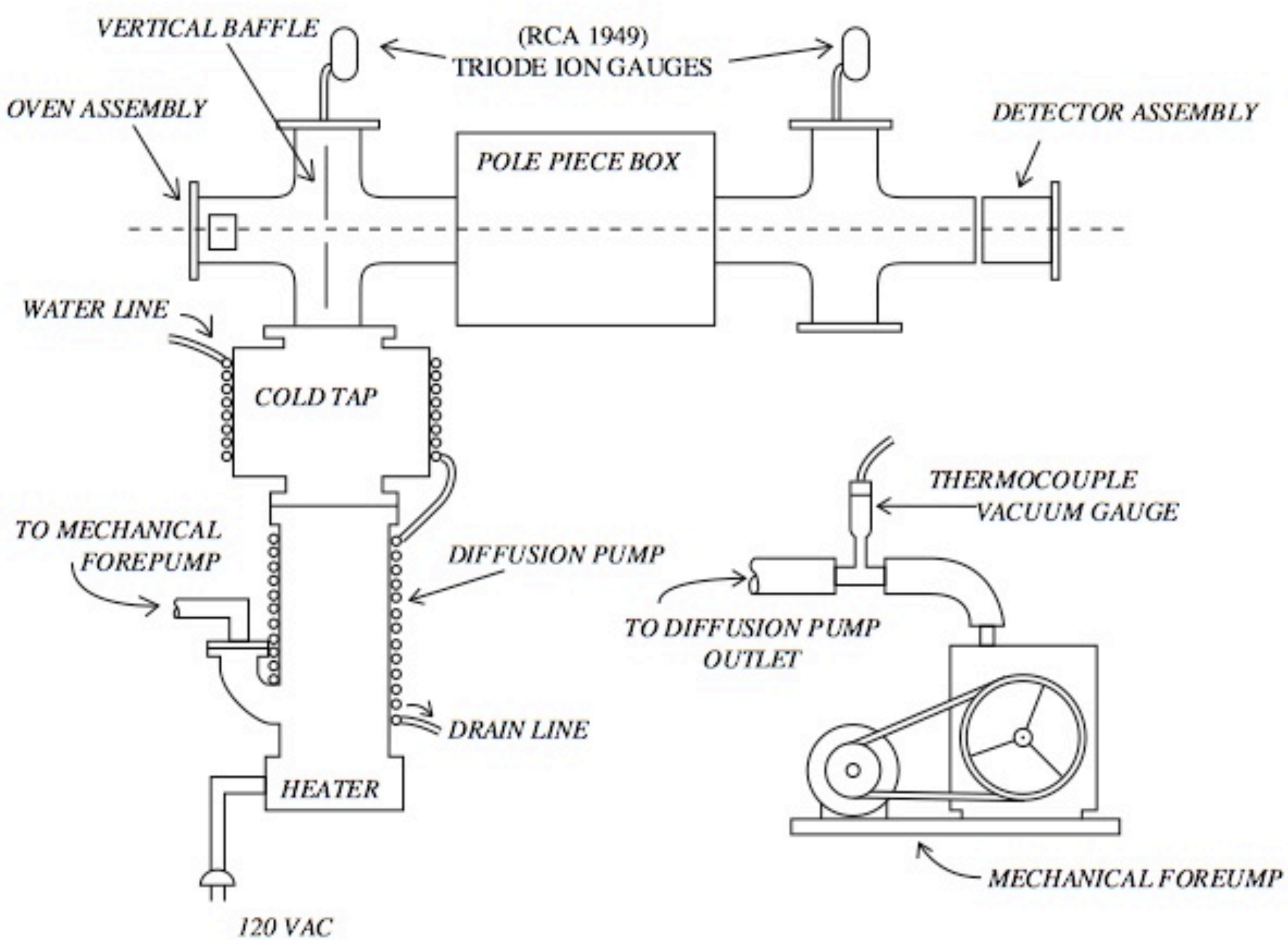
Proposal

Carry out similar experiments using massive particles such as electrons and neutrons with a view of demonstrating weak measurement and exploring the existence and nature of the quatum potential .

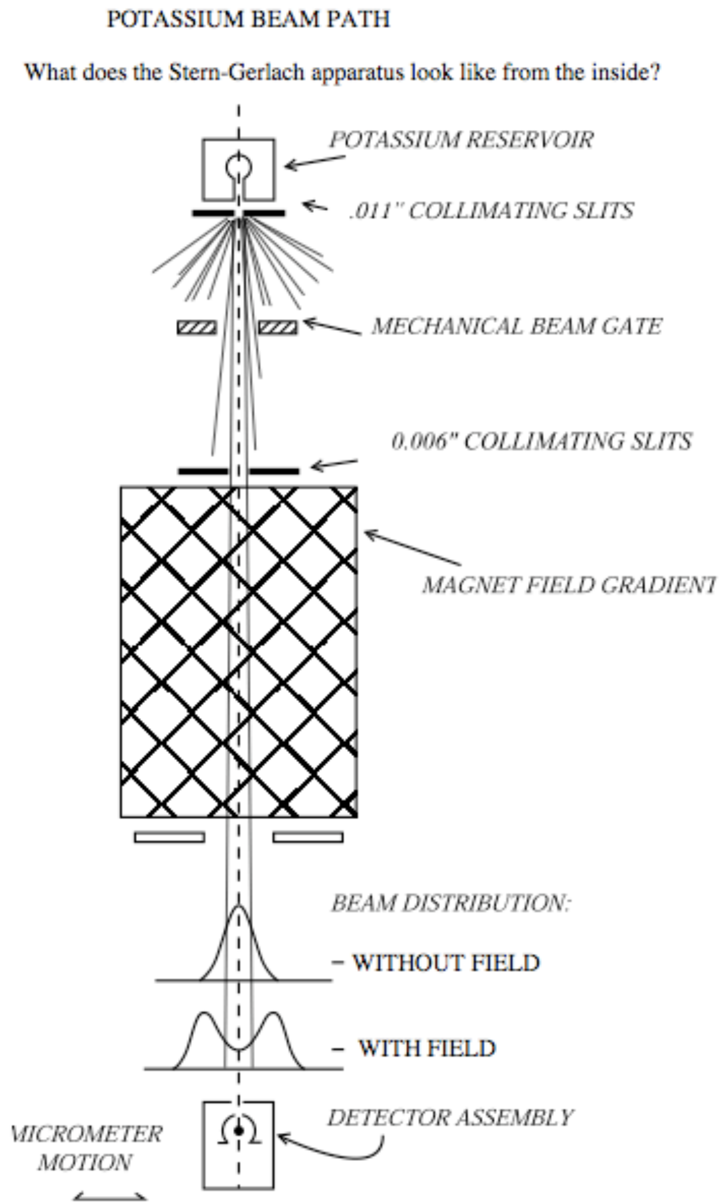
The first step is to build a Double Stern-Gerlach experiment and show that the weak measurement principle works for massive particles.

The second step would be to build a 2-slit experiment and map the trajectories of massive particles. Then attempt to reconstruct the quantum potential to see if it fits the Bohm prediction.

S-G using potassium atoms - 1



S-G using potassium atoms - 2



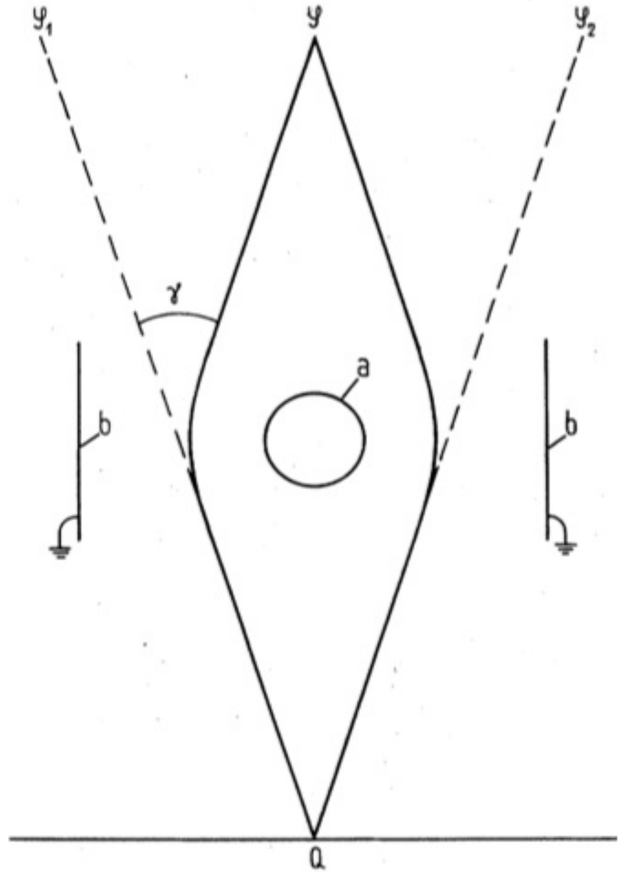
Electrons in the 2-slit experiment

Mollenstedt and Duker. Zeitschrift fur Physik, 145 S:377-397, 1956.

Mollenstedt used an electrostatic biprism as the 2-slits used in Young's experiment.

The 10 - 20keV electron beam enters at the top at "y".

The biprism consists of a gold covered quartz fibre, "a" , diameter of 2.5 mm and 6 mm in length, set vertically and equidistant between two grounded conductors, "b", 4 mm apart. The fibre was held at a potential of 10 V.

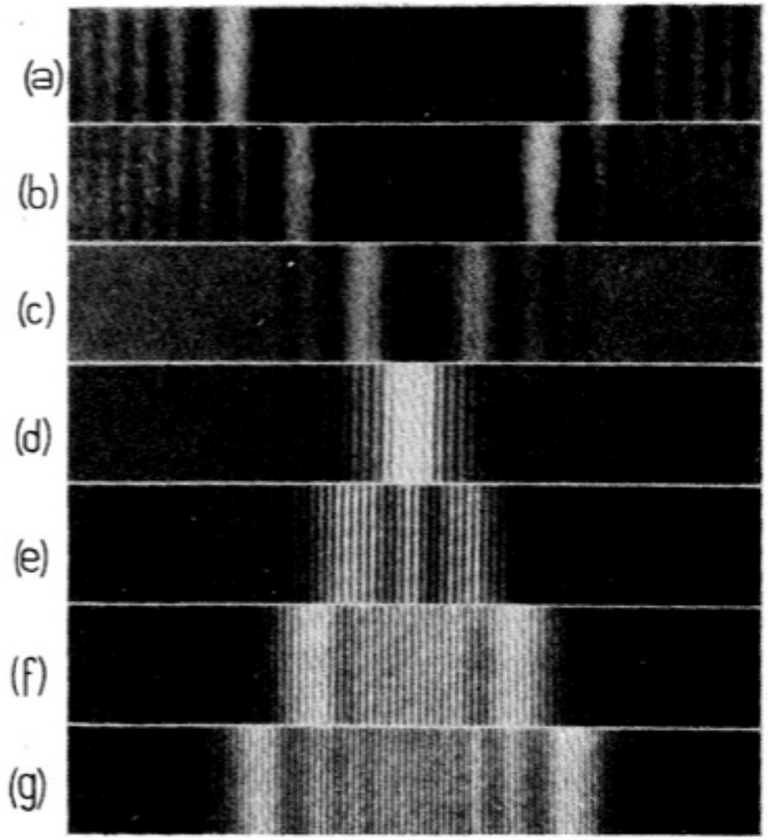


The working region estimated 15 μm from the fibre.

Observation of the interference fringes for electrons

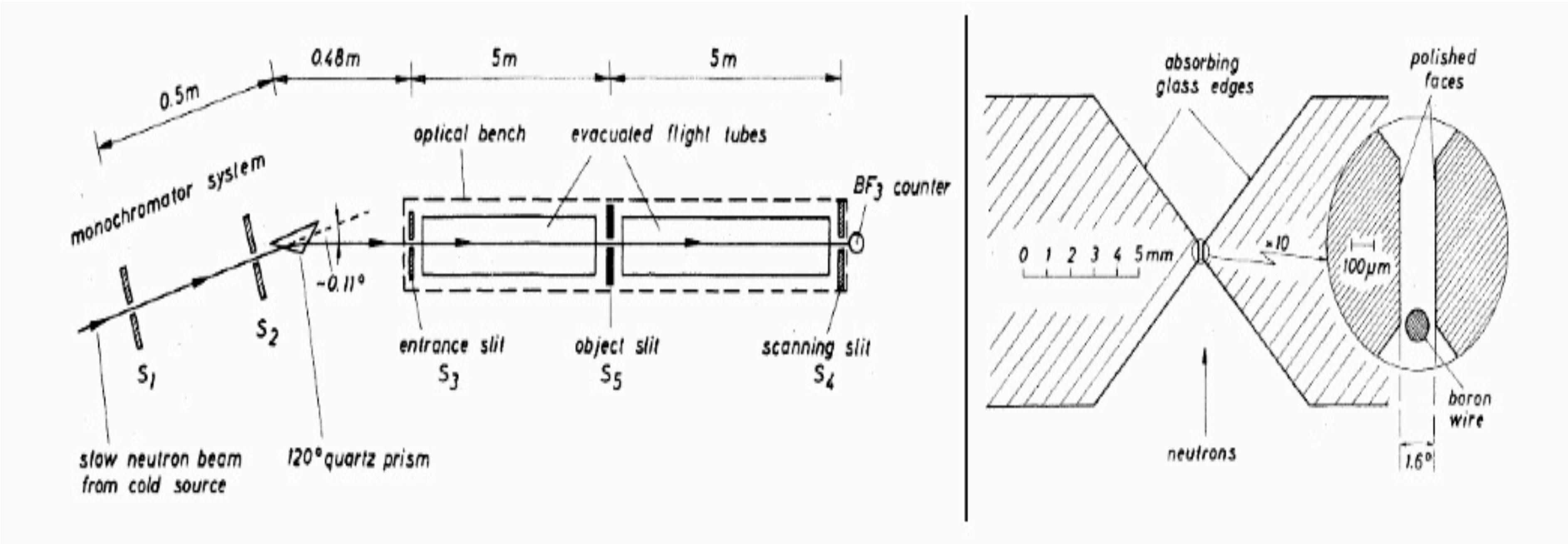
Effectively the biprism produces two virtual images of the filament emitting the electrons.The interference pattern is obtained as the superposition of the electron waves arriving in the observing plane.

By adjusting the voltage on the on the fibre the interference pattern gradually comes into sharp relief.



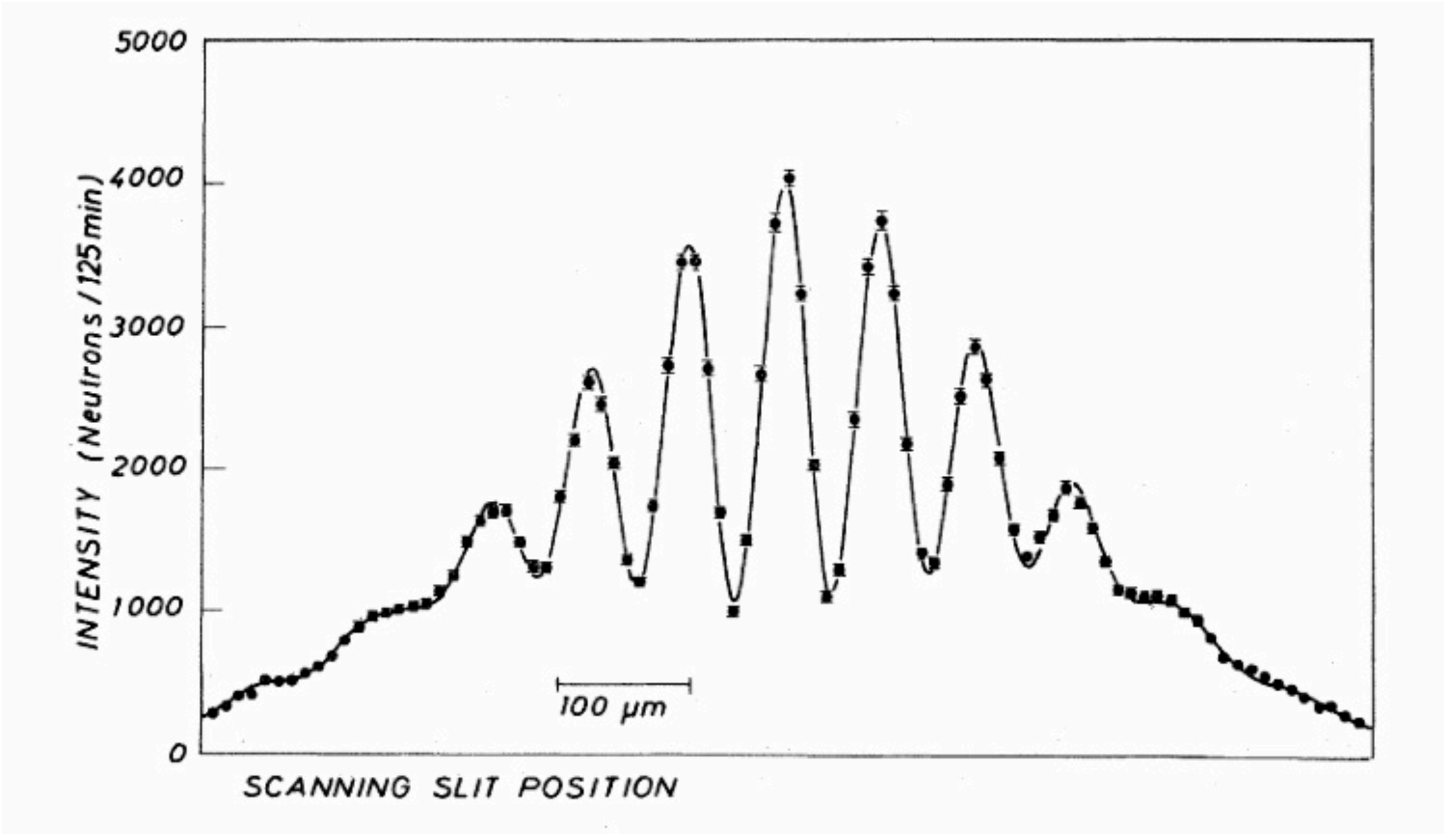
Neutron 2-slit experiment

Zeilinger et al. Rev.Mod.Phys., 60:1067−1073, 1988.



The neutrons are selected and focused onto a slit similar to that used by Mollenstadt.

Measurement of position of neutrons



BF_3 detectors were used to scan across horizontally and the number of neutrons were counted at regular intervals.

If a weak measurement was carried out between the slits and the BF_3 detectors then it should be possible to map out the trajectories.

Conclusion

Basil has shown the history of Bohm's interpretation and the introduction of the quantum potential and its possible use in nano-technology. He also reported the objections of Bohr, Heisenberg and Pauli to the whole approach. Their objections make people think it is in some way illegitimate.

The theory of the weak values was explained in detail and its possible use in directly observing the quantum potential.

We have explained the difference between a weak and strong measurement and how particle physics uses weak measurement without realising it.

The principle of weak measurement has been observed using photons in:

- An analogue of double Stern-Gerlach experiment.
- A Young's 2-slit experiment.

We want to further explore experimentally the weak values using massive particles such as electrons and neutrons.

Weak measurement of an operator A involves inducing a phase change in the wave function which is revealed in a strong measurement of a complementary variable B.

Recently there has been considerable interest in the new notion of a 'weak measure-ment' introduced by Aharonov, Albert and Vaidman [1] [2] to reveal more details ofquantum processes than the traditional Von Neumann or strong measurement [8]. Thestrong measurement involves the collapse of the wave function in the final stage of theexperiment producing an eigenvalue of some operator A; weak measurement of the
op- erator A
involves inducing a phase change to
the wave function which can ultimately
be revealed in a strong measurement of
a different complementary operator B.
In this way we can gain new, more subtle
information about quantum systems.