Presentation:

# Background / Introduction

* Since its development at the turn of the 20th century, Quantum Mechanics has vexed physicists.
* Einstein and his colleagues were particularly concerned with the implications of quantum entanglement and the fundamental uncertainties that underline quantum mechanics and constructed what is known as the EPR paradox to discredit the physicality of quantum theory.
* The EPR paper prompted so-called "Hidden Variable" theories, which no longer required the fundamental uncertainties. These theories were characterised in juxtaposition to quantum mechanical theories by **locality**, whereby separated systems could not affect each other, and **determinism**, whereby a definite knowledge of a state would allow for accurate predictions for the evolution of that state.
* John Bell was able to design and perform a test that would contradict these theories. Bell built an object called the “Bell Parameter”, denoted as E or P, representing the average result of the product of two non-local tests and with this, was able to show that if such “Hidden Variables” existed, then changing the experimental settings could only change this Parameter in a bounded way. This created an inequality that “Hidden Variable” theories must satisfy, known as Bell’s inequality.
* This work was expanded by Clauser, Horne, Shimony and Holt in 1969 who created an object called the CHSH Bell Parameter , built off rates of coincidences, which they showed must have a magnitude less than 2. Lewis-Swan and Kheruntsyan were also able to show that the Bell Parameter E should be sinusoidal in phi and this must have an amplitude equal to in order to provide a CHSH Bell Parameter greater than 2 and hence produce a violation.
* Many tests have been done with massless particles like photons that violate this inequality and justify the completeness of quantum mechanics for these optical systems. However, equivalent violations using atomic, and so massive, systems has so far proven elusive. Such a violation test would be a milestone in the development of quantum physics and has potential implications and applications in branches such as quantum metrology and exotic theories like gravitational decoherence and quantum gravity theories.
* The present study seeks to assess the suitability of performing such a test with an atomic system, using entangled momentum states. To do this a simulation of the experimental set-up was established and correlators were built that could generate our Bell Parameter E for different phases. The effect of experimental sources of error, such as low resolution in detectors, lost detections due to poor quantum efficiency and dark counts from non-experimental sources, was examined to investigate the conditions under which a Bell violation would be observable. Finally a classical simulator was built to ensure that any detected behaviour which resembled quantum behaviour could not be the result of a biased classical system.

# Method / Set up

* The study simulates a Rarity-Tapster scheme (pictured). Here, metastable Helium-4 is manipulated with magnetic fields to give it a ‘kick’ in both vertical directions. As the Bose-Einstein condensate evolves, individual atoms will scatter creating entangled momentum states, diametrically opposite on the sphere, here one such pair in each sphere is denoted with a, plus and minus, and b, plus and minus. One half of each sphere is then phase shifted with a fine beam, in accordance with the Rarity-Tapster schematic. These spheres are then reflected with a Bragg pulse to super impose again and another Bragg pulse causes the two spheres to interfere. Particles in a+ and b+ will interfere with each other and exist in a superposition between the two spheres, the same process simultaneously occurs with their entangled partners in a- and b-. The spheres are then left to evolve again in this superposition and particle detections can occur. In this way, an analogue for the optical Bell tests is constructed for an atomic system.
* The probability of a state for any particular mode quadruplet can be derived from the physics of the system, dependent on the mode occupancy and the two phases and . The calculations were done courtesy of **Kieran** and it was discovered that the probability depends only on the sum of the two phases so we can simplify our model to just one global phase shift .
* The present study simulates this system by generating a large number of states, in their respective probabilities. Each of these states correspond to a certain number of particles in each port (Y, X, W and Z) and each particle is mapped to the vertices of a rhombus, such that Y and W are at opposite points on the upper sphere and W and Z sit at the equivalent points on the lower sphere. Each generated state is mapped to a different, random rhombus. In this way we simulate detections across the spheres to recreate the detections that will take place in a laboratory experiment.
* *Explain ports + phase shift.*
* We then measure coincidences between the four ports by constructing histograms of the distances between detections. We do this both within an individual port quadruplet, and across every simulated trial and divide these to get a normalised g2 correlator, which represents the rate of coincidences between two ports.
* These coincidences between the four possible modes are then used to construct our Bell Parameter, E, for the given phase shift. This process was repeated for different phase shifts and plots of the resultant Bell Parameter dependence were generated.
* This data was analysed and a sinusoid was fitted to each set of data, with the amplitude of this function serving as our E0.
* To simulate the effects of quantum efficiency we removed detections at random leaving only the percentage of points that was desired. Different plots of the Bell Parameter were modelled for different quantum efficiency rates, to investigate the dependence of the amplitude E0 on the quantum efficiency.
* To simulate dark counts, detections were added at random in each simulated trial with a probability given by the dark count rate. This rate was varied and its effects on the amplitude E0 were measured.
* To simulate the resolution of our detectors, points within a simulated trial were mapped to points near the vertices of the rhombus, with a random gaussian distribution around each vertex. The decay width of this gaussian as a fraction of the radius of each sphere was denoted B or and was varied to again determine the dependence of our amplitude E0 on this resolution.
* In order to model a biased classical beam-splitter, we developed alternative probabilities for the classical case that could vary with different biases for each beam splitter. The same simulation and correlation codes were used on the classical probabilities and the individual g2 correlators and Bell Parameter E were investigated under different bias conditions.

# Results / Discussion:

* In this study it was shown that there was minimal impact on the amplitude E0 of our Bell Parameter arising from lost counts from quantum efficiency, however the lower QE rates corresponded to much higher noise and a larger uncertainty in the amplitude that we find. Similarly the resolution of our detectors had a minimal effect on the magnitude of our Bell Parameter, only contributing to the noise and hence increasing the uncertainty of our measurement.
* Dark Counts however could be seen to have a much larger effect, with a Bell violation impossible at dark count rates of even a few percent. However, in an experimental setting it is reasonable to have this rate at values of only one part in a million, which is sufficiently small that a violation should still be observable.
* For the classical beam splitter we found that there was no strong phase dependence on the Bell Parameter, as expected. It was also evident that for a given set of biases, the correlators only varied slightly around a fixed, constant value. This means that any varying behaviour that is detected in an experimental set up can not arise from a classical system and can only be justified by quantum interference.

# Conclusion

* This study successfully modelled a quantum and classical rarity-tapster interferometer with momentum entangled atomic states.
* We were able to show that even with generous amounts of noise, that this experimental system should resolve a Bell violation.
* Further we were able to show that a classical beam splitter, even with biases should not produce any behaviour that appears as a quantum system, thus ensuring that any observed violation or signs of quantum behaviour are in fact the result of the fundamental quantum behaviour of this system.
* The study sought to simulate the experimental system as accurately as possible however a few more explorations could be developed. Notably, the phase shift that is applied to the helium is not uniform across each sphere and in fact will vary slightly over particles with different momenta. Future simulations which factored this phase shift gradient could be important in justifying the validity of any potential Bell violations. One might also consider the fact that we will not have perfect interference between opposite momenta states (a+ and b+ in the previous diagram), these states will also interfere slightly with nearby momenta states on both halos. The effect of this effect on resolving a Bell violation would also be relevant to study, however we believe that these effects should be less significant than the noise sources studied in this project.