Event-by-event simulation of neutron interferometry experiments*

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*Work done in collaboration with
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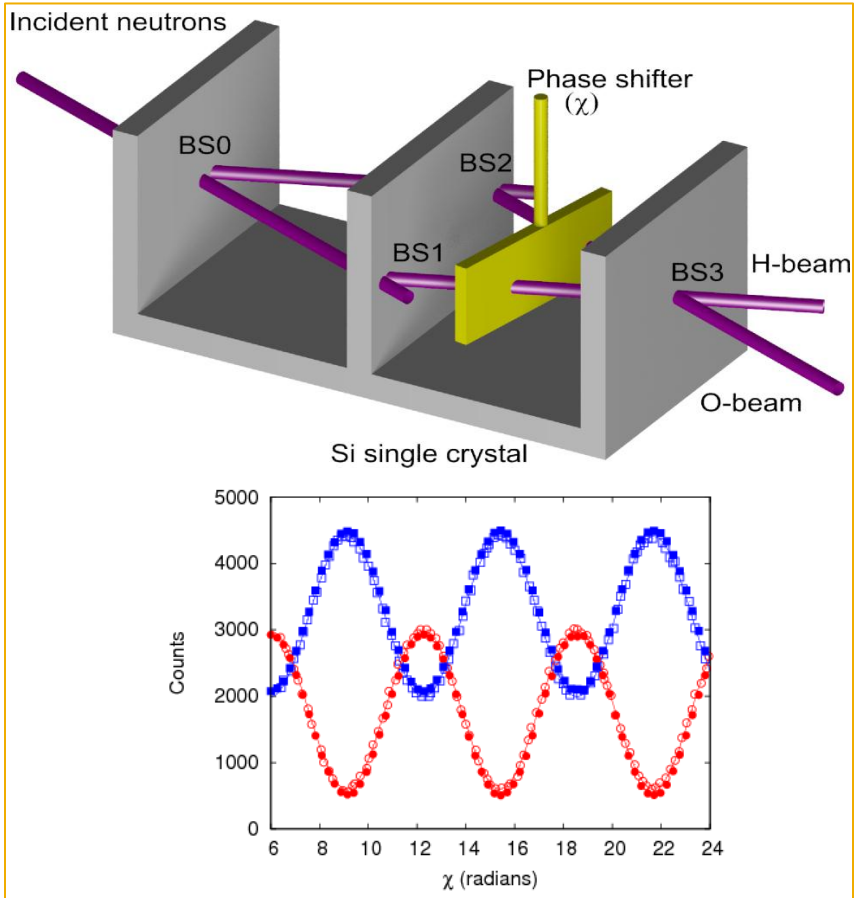
Content

- Introduction
  - Statement of the problem
  - General aspects of event-based simulation
- Event-based model: Realization
- Application: Single-neutron interferometry
- Conclusion

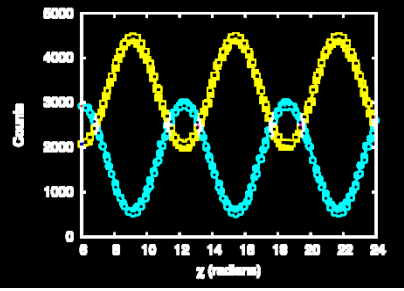
Perfect crystal neutron interferometry experiment

- Neutrons enter from the left, one at a time
- Neutrons in the O(H)-beam trigger a nuclear reaction, producing a “click” of one of the detectors
- The neutron counts in the O(H)-beam change with the position of the phase shifter changes
- The results are interpreted as interference of waves

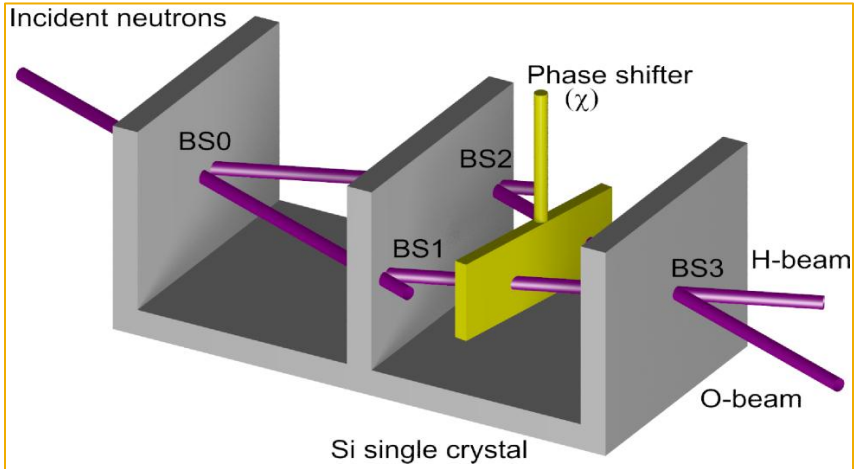


G. Kroupa et al., Nucl. Instrum. Methods Phys. Res. A. 440, 604 (2000)

Quantum theory: Neutron = wave packet ?

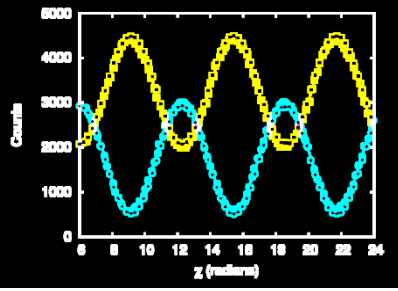


- A neutron enters the interferometer from the left and is “split” in two parts by BS0
- Each part is split in two again at BS1 and BS2, giving four parts
- Two parts fly of to infinity
- The two remaining parts “reunite” at BS3
- Two parts emerge from BS3
- One part out of four triggers a nuclear reaction that produces a “click” of one of the detectors

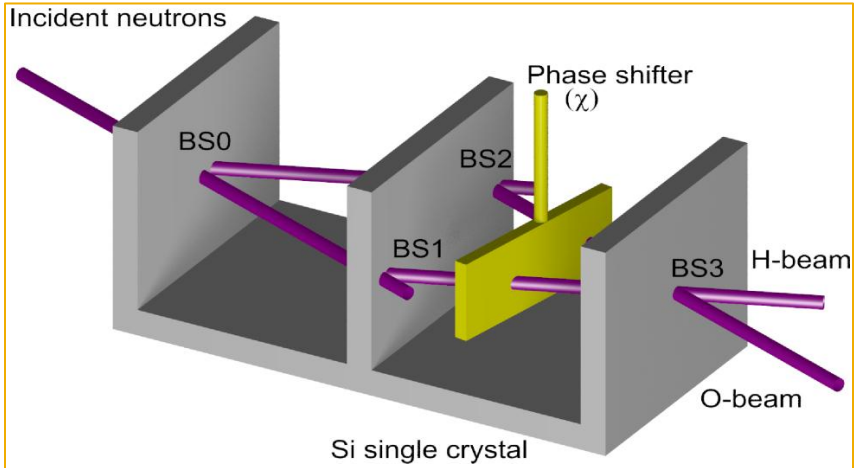


- Feynman: The observation that the interference patterns are build up event-by-event is impossible, absolutely impossible to explain an any classical way and has in it the heart of quantum mechanics. In reality it is the only mystery.

Quantum theory: Statistical interpretation



- One probability wave, representing the collection of all neutrons, propagates through the interferometer according to the rules of quantum theory
- The probability of triggering a nuclear reaction producing a “click” of one of the detectors is almost the same as the probability that a neutron emerges from BS3 in the O(H)-beam
- No magic, no mystery, no strange logic but…
- Probability distribution ➔ event?



- Leggett: In the final analysis, physics cannot forever refuse to give an account of how it is that we obtain definite results whenever we do a particular measurement

This talk:

- Can we construct logically consistent, cause-and-effect models of the definite results observed in experiments?
  - YES, so far it seems so
    - Cause-and-effect modeling → Einstein local causality
      - Overview: K. Michielsen, F. Jin, and H. De Raedt, "Event-based Corpuscular Model for Quantum Optics Experiments", J. Comp. Theor. Nanosci. 8, 1052 - 1080 (2011)
- Is NOT about the validity, extension, applicability or about interpretations of quantum theory

Basic ideas

- Search for a logically consistent, cause-and-effect description of the definite results (events) that constitute the experimental facts
  - From events to probabilities, not vice versa!
    - Description cannot be based on the knowledge of the probability distributions to observe events
    - May not fit into classical Hamiltonian mechanics
  - Perception → events → mathematical description
    - No need for an “objective”, mathematical, world picture

Change of paradigm

- Traditional theoretical modeling
  - Behavior of systems is described in terms of traditional mathematics
    - Differential equations, probability theory, …
- Discrete-event approach
  - Behavior of systems is described by simple rules
    - Collectively, such systems may exhibit complex behavior
    - Examples:
      - Lattice Boltzmann model: flow of (complex) fluids
      - Cellular automata: S. Wolfram, “A new kind of Science” (2002)

Event-by-event simulation

- Discrete-event simulation:
  - Model physical phenomena as a chronological sequence of events
  - Events: Action of the experimenter, particle emitted by a source, signal generated by a detector, particle impinging on material,…
- Basic idea: Try to invent an algorithm that
  - Uses the same kind of events (data) as in experiment
  - Reproduces the statistical results of quantum theory without making use of this theory

Event-by-event simulation

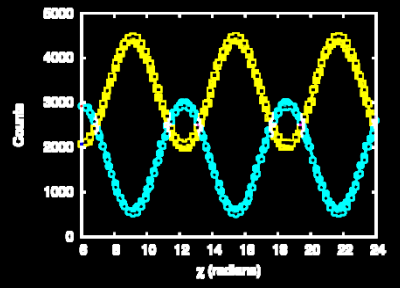
- A cause-and-effect simulation on a digital computer is a “controlled experiment” on a macroscopic device which is logically equivalent to a mechanical device

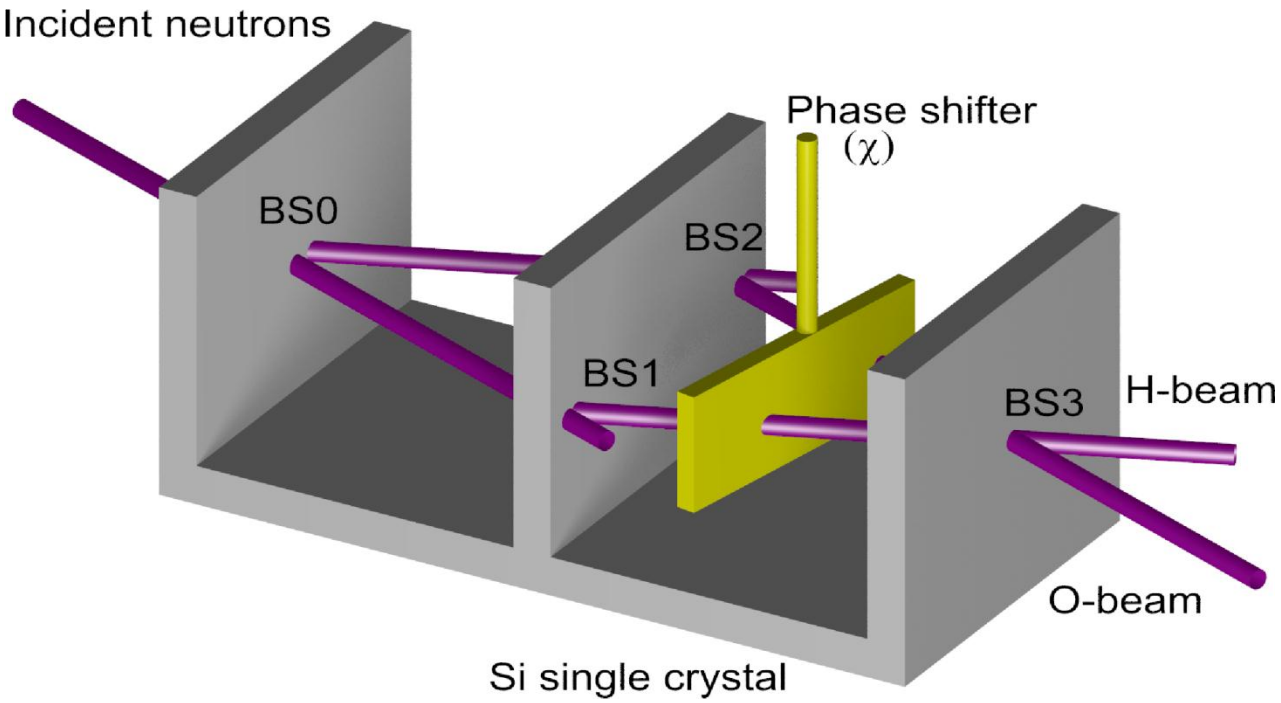
Babbage difference engine
by Andrew Carol
http://acarol.woz.org

Event-by-event simulation

- An event-by-event simulation that reproduces results of quantum theory
  - Shows that there exists a macroscopic, mechanical model that mimics the underlying physical phenomena
    - N. Bohr: “There is no quantum world. There is only an abstract quantum mechanical description.”
  - Provides an “explanation” and “understanding” of what is going on in terms of elementary events, logic and arithmetic

Application: single-neutron interferometry experiments

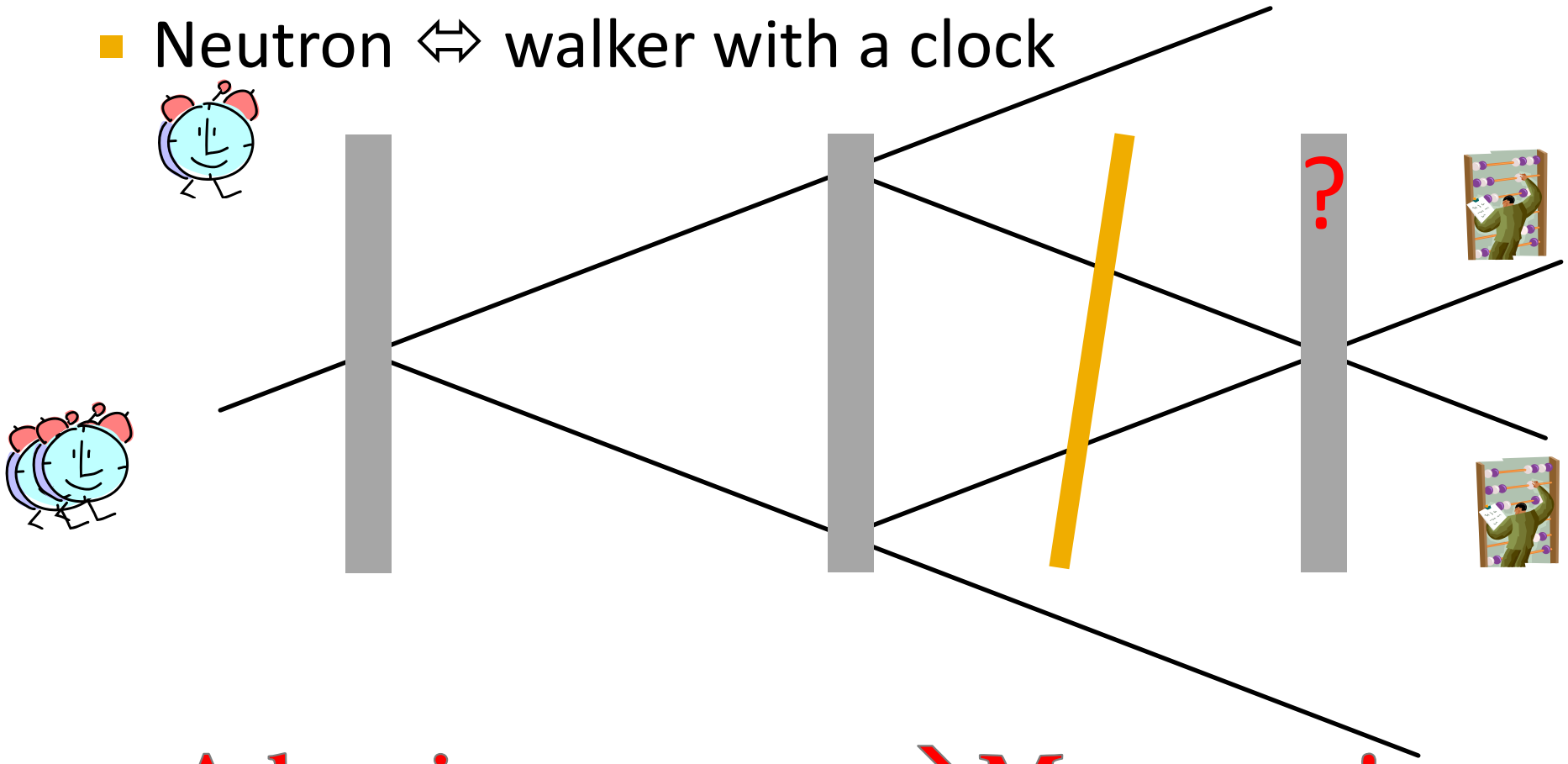




- H. Rauch, W. Treimer, and U. Bonse, Phys. Lett. A 47, 369 (1974)

Changing the paradigm…

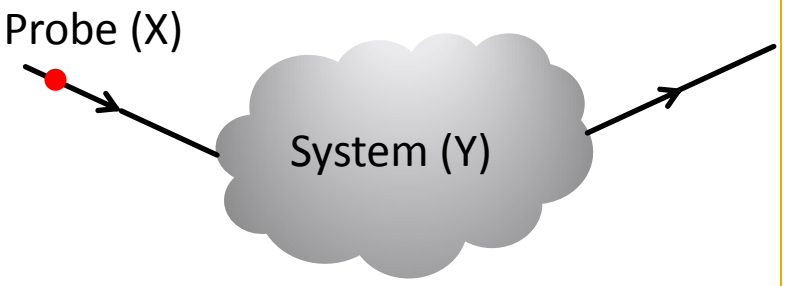
- Neutron ⇔ walker with a clock



Adaptive system → Memory !

What "memory" ?

- Generic experiment



- Probe is represented by variable X
- System is represented by variable Y

- For simplicity, assume equation of motion is linear

$$\frac{d}{dt}\begin{pmatrix} X \\ Y \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix}\begin{pmatrix} X \\ Y \end{pmatrix}$$

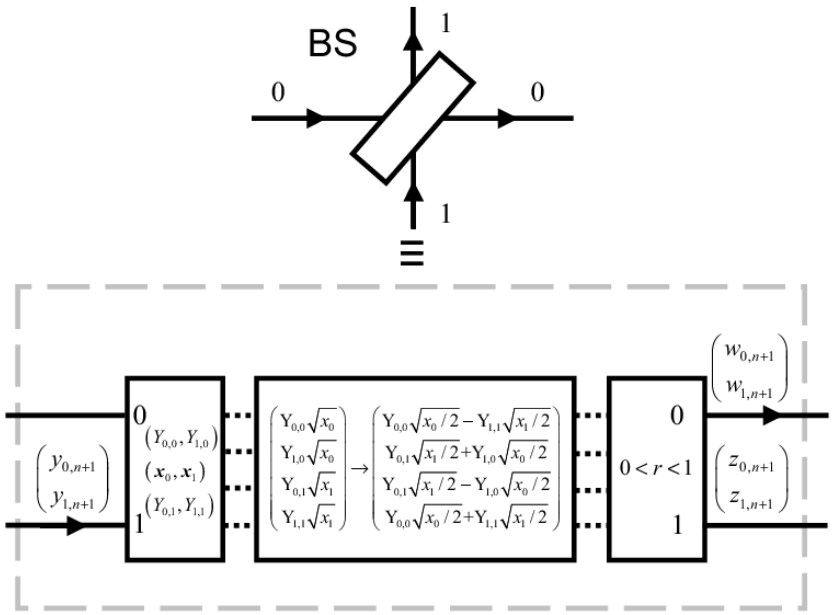
- Solution for the probe

$$\frac{dX(t)}{dt} = AX(t) + \int_0^t \underbrace{Be^{D(t-u)}C}_{\text{memory kernel}} X(u)du + Be^{Dt}Y(0)$$

- Generic for all current models in physics
  - Newton, Maxwell, quantum,…

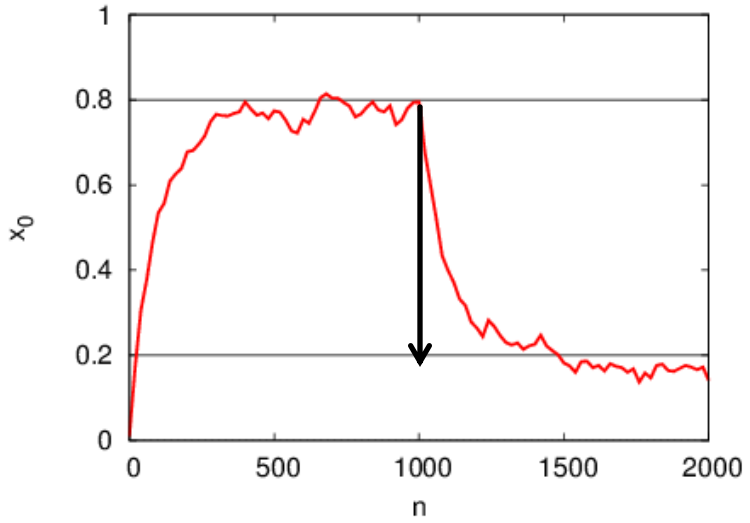
Realization: Deterministic Learning Machine

- Algorithm (example)
  - $(Y_{0,1},Y_{1,1}) \leftarrow (y_0,y_1)$
  - Example: Input on port 1
    - $x_0 \leftarrow \alpha\, x_0$
    - $x_1 \leftarrow \alpha\, x_1 + 1-\alpha$
      - α : control parameter
      - $x_0 + x_1 \le 1$
  - Apply transformation → (w_0,w_1,z_0,z_1)
  - If $(w_0)^2+(w_1)^2 < r$ send "0" event, otherwise send "1" event



What does the machine do?

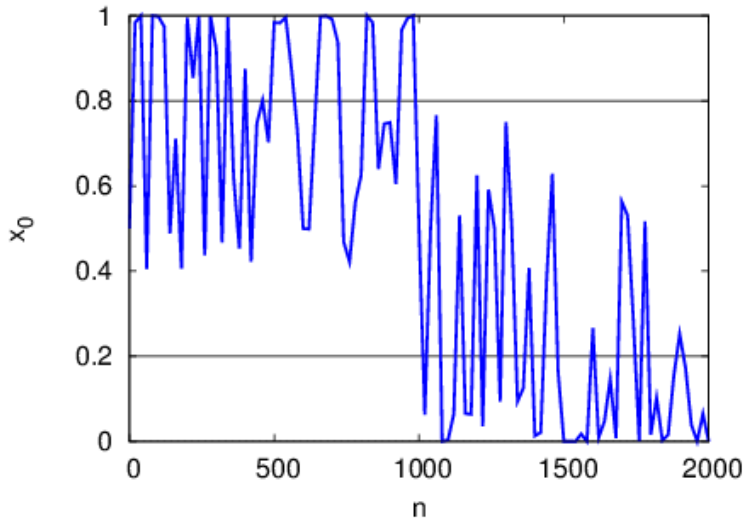
- Start with $x_0 = x_1 = 0$
- Assume input on port 0 with frequency 0.8
- After 1000 input events this frequency changes to 0.2
- Machine adapts, "learns" the ratio of 0 and 1 events without counting



- $\alpha = 0.99$
- $\alpha \rightarrow 1^-$ ➔ reproduces results of quantum theory

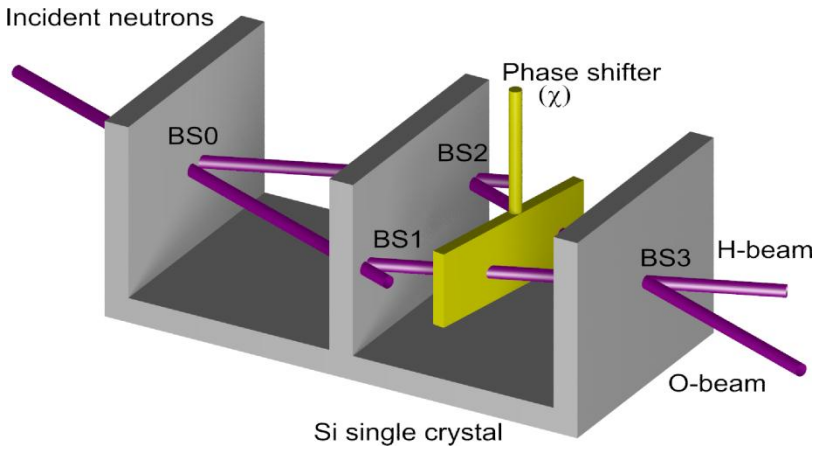
What does the machine do?

- Start with $x_0 = x_1 = 0$
- Assume input on port 0 with frequency 0.8
- After 1000 input events this frequency changes to 0.2
- Machine adapts, "learns" the ratio of 0 and 1 events without counting



- $\alpha = 0.5$ instead of 0.99
- Still reproduces results of quantum theory but with less visibility, …

Laue-type interferometer: Event-based model

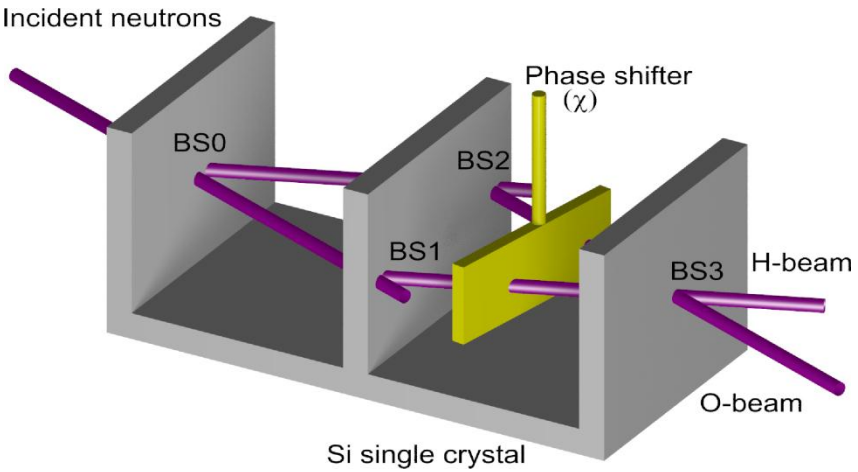


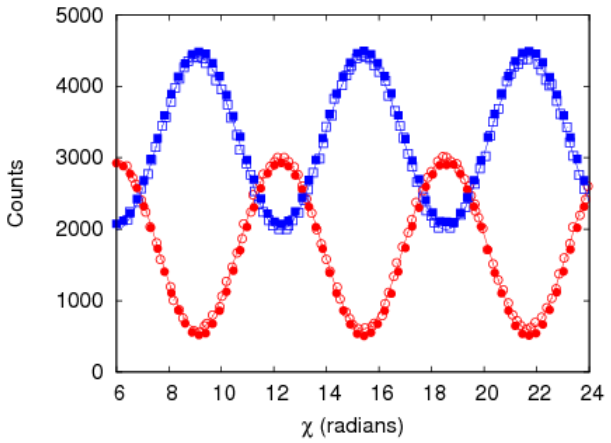
- H. Rauch, W. Treimer, and U. Bonse, Phys. Lett. A 47, 369 (1974)
- Event-based model = one-to-one copy

- Neutron: Particle carries a clock to measure the time of flight
- BS0,…BS3: copies of the deterministic learning machine
- Phase shifter: changes the time of flight
- Detector: counts every particles that arrives at its input gate

Laue-type interferometer

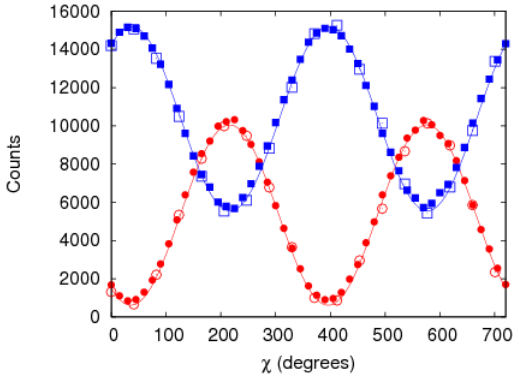
H. Rauch, W. Treimer, and U. Bonse, Phys. Lett. A 47, 369 (1974)





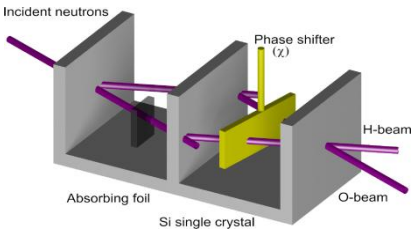
Reflection coefficient = 0.22,
DLM parameter $\alpha = 0.5$,
10x5000 particles per angle.
Circles: O-beam, squares: H-beam.
Solid symbols: Simulation.
Open symbols: Experimental data extracted from Fig.2 in G. Kroupa et al., Nucl. Instrum. Methods Phys. Res. A. 440, 604 (2000)

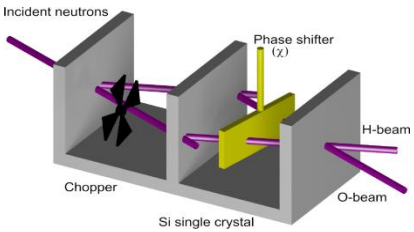
Data provided to us by
H. Lemmel and H. Rauch.
Data set: rasterB1_3_1.dat
Reflection coefficient = 0.22,
DLM parameter $\alpha = 0.7$,
16000 particles per angle



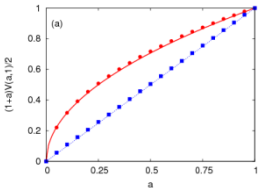
Not an accident…

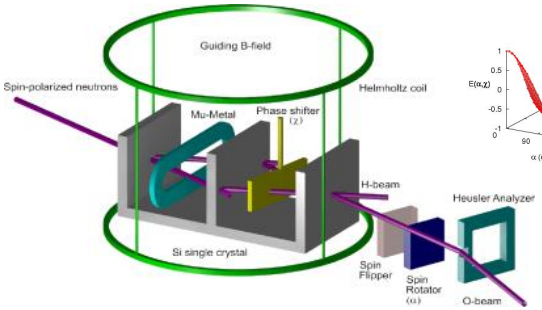
- The same components (algorithms) have been used to simulate

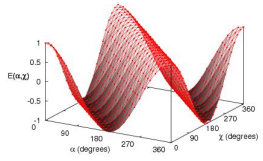


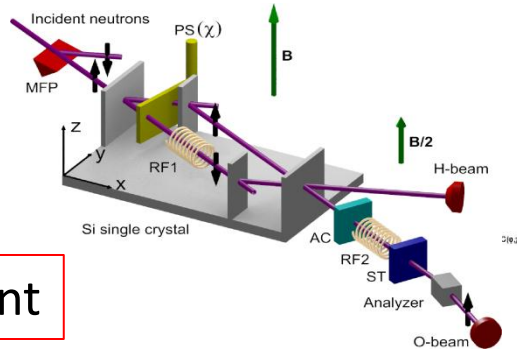


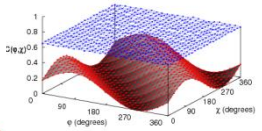
H. Rauch and J. Summhammer, Phys. Lett. A 104A, 44 (1984)











entanglement

Y. Hasegawa, R. Loidl, G. Badurek, M. Baron, and H. Rauch, Nature **425**, 45 (2003)

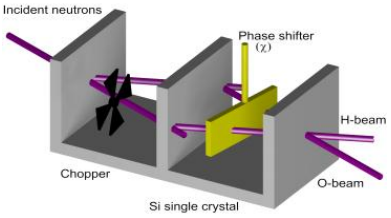
S. Sponar, J. Klepp, R. Loidl, S. Filipp, G. Badurek, Y. Hasegawa, and H. Rauch, Phys. Rev. A 78, 061604 (2008)

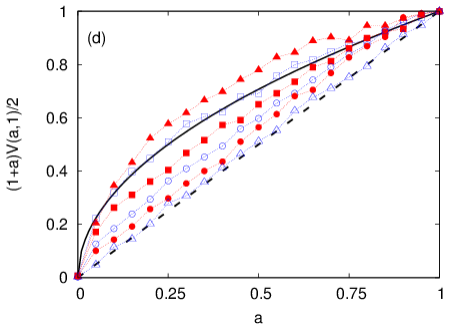
using particles only, without first solving a wave equation

Do these event-based models predict new features?

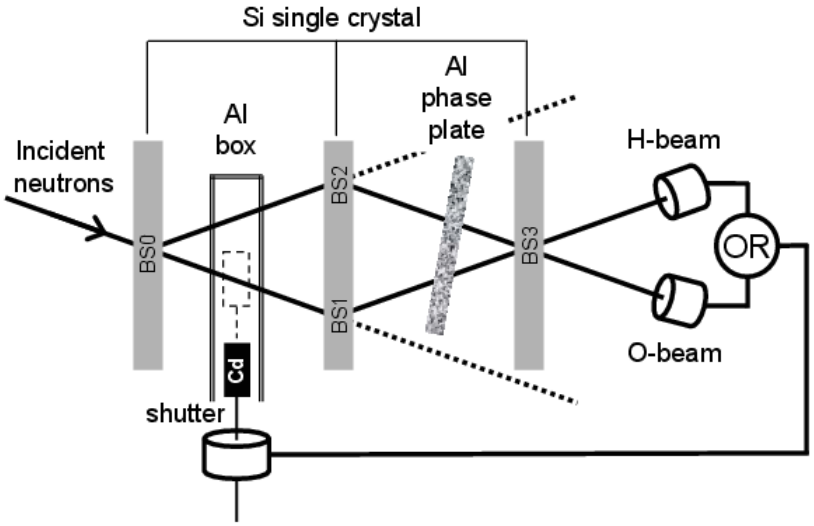
- It is futile to test our event-based models in the stationary regime of many events
  - In this regime, the event-based models reproduce the results of quantum theory with an accuracy that is far beyond what experiments can probe

- To refute one of these models, experiments should operate (take data) in a non-stationary regime
  - H. Rauch and J. Summhammer (1984)





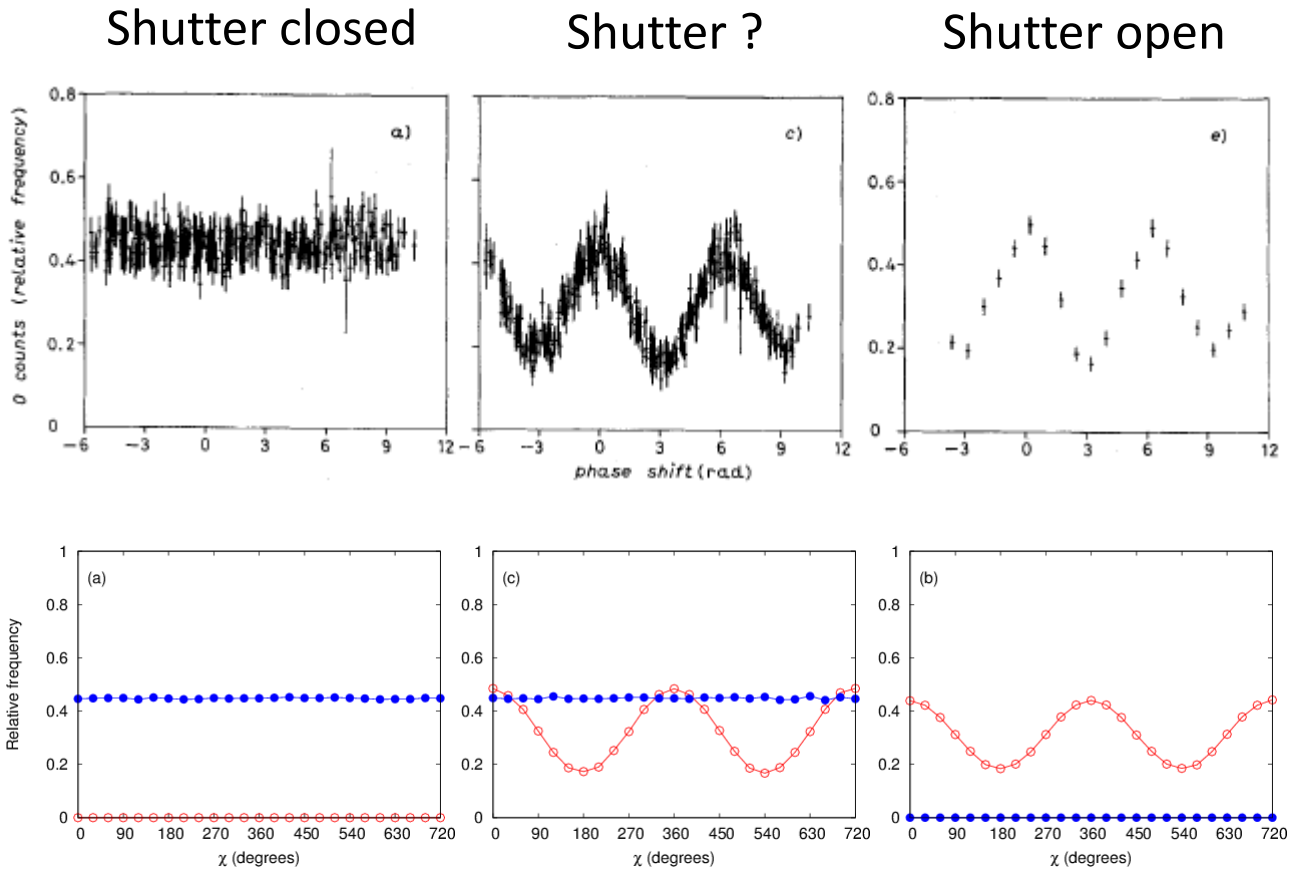
Summhammer's experiment



- J. Summhammer
  - Nuovo Cimento. B 103, 265 (1989)
- Originally conceived to test the non-ergodic interpretation of quantum theory
  - V. Buonomano, Nuovo Cimento B **57**, 146 (1980)

- Neutrons transmitted by BS0 may be blocked by a shutter
- For each detected neutron the state of the shutter changes with probability ½
- Detection events are labeled by the state of the shutter (open or closed)

Summhammer's experiment: Event-based simulation



J. Summhammer, Nuovo Cimento. B **103**, 265 (1989)

- Quantitative agreement!

Interference and entanglement with photons

- The same components (algorithms) have been used to simulate
  - Optics of interfaces, parallel plates, multilayers, …
  - Two-beam interference experiments
  - Mach-Zehnder interferometer experiments
  - Wheeler's delayed choice experiment
  - Quantum eraser experiment
  - Single-photon tunneling experiment
  - Einstein-Podolsky-Rosen-Bohm experiments with photons
  - Hanbury Brown-Twiss experiments
  - Universal quantum computation, quantum cryptography

using particles only, without first solving a wave equation

- K. Michielsen, F. Jin, and H. De Raedt, J. Comp. Theor. Nanosci. 8, 1052 - 1080 (2011)

Conclusion

- We have invented a systematic, modular procedure to construct causal, Einstein-local, classical (non-Hamiltonian) discrete-event simulation models of interference and entanglement
  - Requires change of paradigm: perception ➔ events ➔ physics, not vice versa
  - No “waves”, “quantum”, or “probabilities” but elementary math + computer simulation
  - Reproduces results of many quantum optics experiments
  - Feynman: The observation that the interference patterns are build up event-by-event is impossible, absolutely impossible to explain an any classical way… In reality it is the only mystery
- Next step: include diffraction/scattering, evanescent waves

Thank you

Published papers, demo's and additional information can be found on www.compphys.net