Teaching Quantum Measurement

An Interactive Stern-Gerlach Simulator for Undergraduate Instruction

Dr. Boris Kiefer — github.com/boriskiefer — linkedin.com/in/boris-kiefer-85089831

The Stern-Gerlach experiment is the canonical demonstration of space quantisation, yet its standard textbook treatment relies on static diagrams that show the result without allowing students to interrogate it. This note describes a minimal interactive simulator — two Jupyter cells, no custom dependencies — that exposes the classical-to-quantum transition directly. Students control thermal noise, field strength, screen distance, and sample size in real time, with a live metrics panel including spot separation, overlap coefficient, and a χ^2 consistency check. A suggested three-step classroom sequence is included. The artifact is freely available and requires no installation beyond a standard scientific Python environment.

Motivation

Undergraduate students arrive at quantum mechanics with a fully formed classical intuition: a beam of magnetic dipoles deflected by an inhomogeneous field should spread into a smooth distribution on a detector screen. The pedagogical challenge is not to correct an error but to engineer a moment of productive surprise — a controlled collision between a confident mental model and a result that cannot be explained away.

Static textbook diagrams do not create this moment. Students see the outcome but cannot interact with the boundary. They cannot ask: *what if the noise were larger? At what field strength does the quantum signature become unambiguous? How many trials are needed before the pattern is statistically trustworthy?* These questions require an interactive model.

Physics Summary

A silver atom ($s = \frac{1}{2}$) passes through an inhomogeneous field. The deflecting force is $F_z = \mu_z \cdot \partial B / \partial z$.

Classical prediction: $\mu_z = \mu \cos\theta$, $\theta \in [0, \pi]$ uniform — a cosine-weighted continuous smear.

Quantum result: $m_s = \pm\frac{1}{2}$, $P = \frac{1}{2}$ each — two discrete spots. The simulator implements both with a single toggle. Three foundational principles are encoded in this single image:

Principle	What the screen shows
Discreteness	Exactly two spots. No continuum.
Probabilistic outcome	Each atom lands in one spot with $P = \frac{1}{2}$; the pre-measurement state is a superposition.
Measurement collapse	An atom measured upper will always remeasure upper along the same axis.

Simulator Design

Four interactive dials via `ipywidgets`:

Dial	Physical meaning	Pedagogical role
N particles	Statistical sample size	When does the pattern stabilise?
Field strength	$\propto \partial B/\partial z$	Primary spot separation control
Thermal noise σ	Transverse velocity spread	Classical-to-quantum transition dial
Screen distance	Drift length post-magnet	Both separation and width scale together

The **classical toggle** is the pedagogical core — switching modes replaces the discrete eigenvalue draw with a cosine-weighted continuous distribution. The contrast is immediate and student-controlled. The **metrics panel** reports spot separation, overlap coefficient, and a χ^2 p-value: not decorative, but a quantitative language for the quality of the quantum signature.

Suggested Classroom Sequence

1. **Classical baseline.** Classical mode, $\sigma = 0.05$, field $= 1.0$. Ask students to predict the outcome before running. The cosine-weighted smear confirms classical intuition. Record the distribution shape.

2. **The quantum surprise.** Switch to quantum mode, identical parameters. Two spots appear. Ask: *why exactly two?* Direct students to the χ^2 panel — the 50/50 split is exact in the limit of large N.

3. **The decoherence dial.** Increase thermal noise to $\sigma = 0.6$. The spots merge. Ask: *has the physics changed, or only our ability to resolve it?* Reduce noise back to 0.05 and watch the signature re-emerge. This introduces decoherence: quantum behaviour is fragile and its observability depends on experimental conditions.

Natural extensions include higher-spin parameterisation ($2s + 1$ spots), sequential measurement stages demonstrating non-commutativity, and numerical integration of the time-dependent Schrödinger equation. All extensions are scoped in the hand-off notes within the notebook.

This document and the associated POC were produced using an AI-augmented workflow with domain-expert human-in-the-loop guidance and verification.