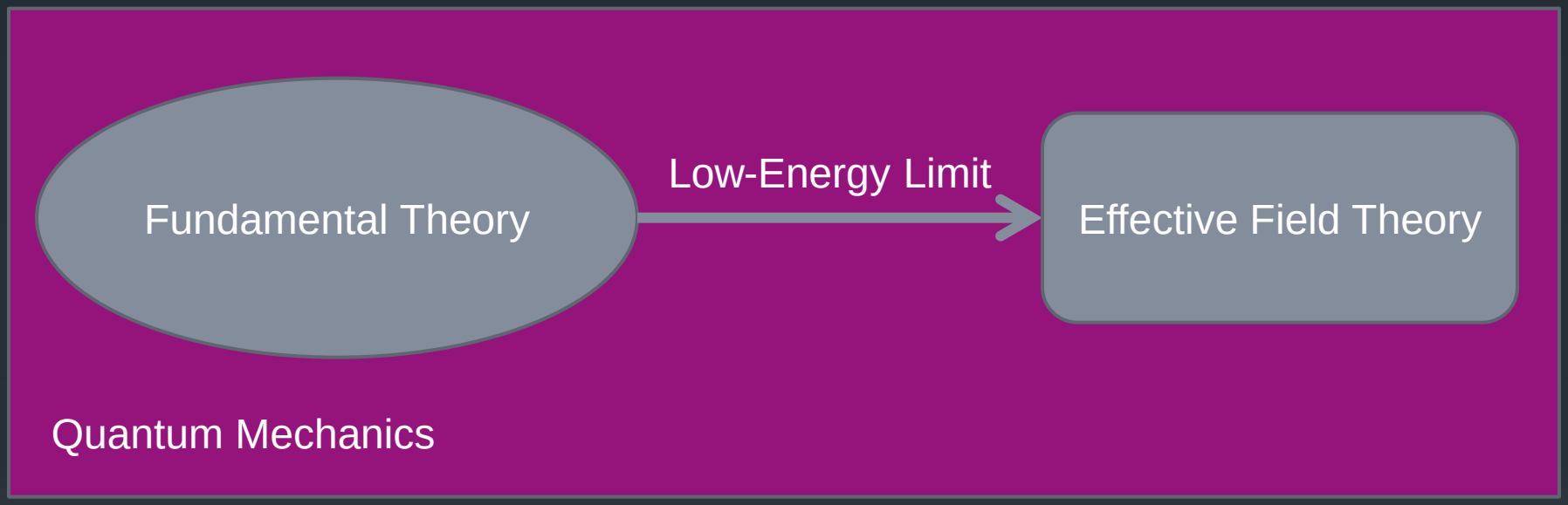
Questioning Quantum Mechanics?

Kurt Barry

SASS Talk

January 25th, 2012

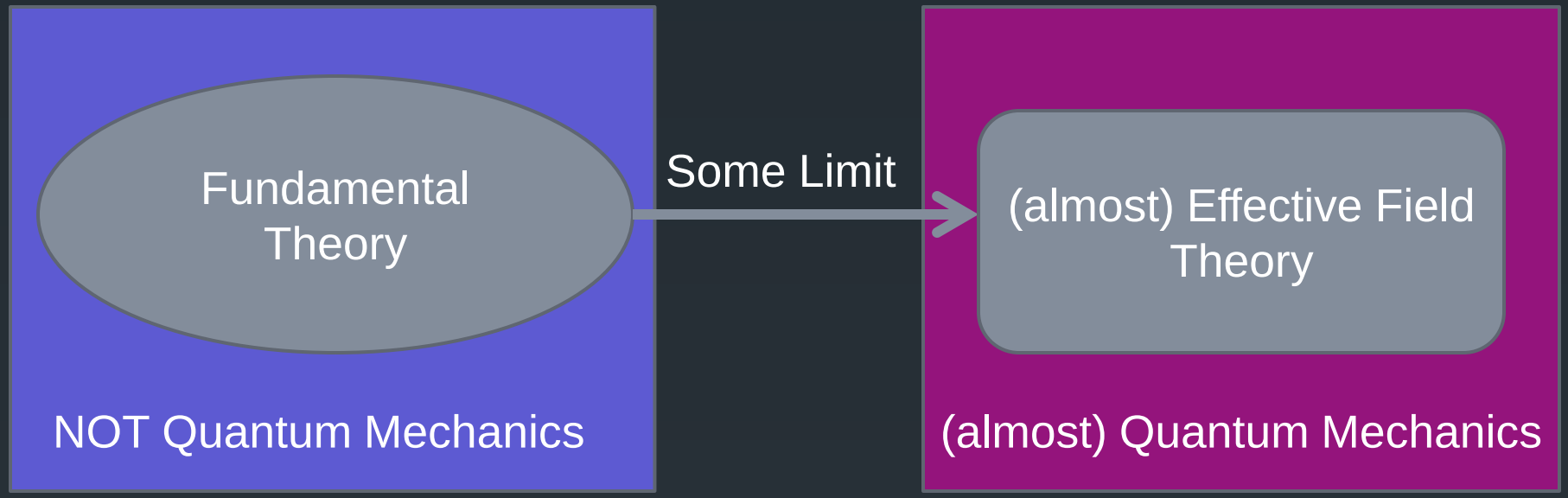
Model of the Universe



Quantum Mechanics is presently the framework for physical law.

What if this isn't the case?

What if:



What deviations from quantum mechanics are possible?

What are their observable consequences?

What Is Quantum Mechanics?

- A state $|\psi\rangle$ is a ray in a Hilbert space
- Probabilities: $|\langle\varphi|\psi\rangle|^2$
- Measured quantities are eigenvalues of Hermitian operators
- **Time evolution described by Schrödinger equation:**

$$i\frac{d}{dt}|\psi\rangle = H|\psi\rangle$$

Linear

Possible generalization: linearity

- Nonlinearity is common in everyday phenomena; why not in quantum systems as well?
- To what extent can we test for non-linearity in a model-independent manner?
- Can we preserve logical consistency in a non-linear quantum theory?

Outline

- Quantum Mechanics from non-linear dynamics?
  - Concrete example: Weinberg's framework.
- Observable consequences of a fundamentally new character?
  - Yes; state-dependent phases, nonlocality. parallel universe communication
- Can a nonlinear theory be logically consistent?
  - Remove nonlocality? (Polchinski, Kibble)
  - Fundamental challenges

Steven Weinberg, Annals Phys. 194 (1989) 336

A Nonlinear Extension: Weinberg's Framework

Making QM Nonlinear

$$i\frac{d\psi_k}{dt} = H_{kl}\psi_l$$

Making QM Nonlinear

$$i\frac{d\psi_k}{dt} = \frac{\partial}{\partial \psi_k^*}\underbrace{\left(\psi_j^* H_{jl}\psi_l\right)}_{\text{real, bilinear function}}$$

Making QM Nonlinear

$$i\frac{d\psi_k}{dt} = \frac{\partial}{\partial \psi_k^*}\left(\underbrace{h(\psi_j^*, \psi_l)}_{\text{real, NON-bilinear function}}\right)$$

One Further Requirement: Homogeneity

- Require that any nonlinear observable a satisfy:

$$a(Z^*\psi^*, Z\psi) = Z^*Za(\psi^*, \psi)$$

- Why?
  - It makes it easy to keep wavefunction's normalization arbitrary
- Now what? Build, build, build.

Achievements

- Constant in time:
  - Wavefunction's normalization, Hamiltonian
- Can find many nonlinear Hamiltonians that respect Galilean invariance
  - Requires taking the standard linear generators for momentum, angular momentum, etc.
- Solutions with harmonic time dependence (stationary states)

What are the observable consequences of Weinberg nonlinearities?

N-atom coherent system, neglecting all but two closely split states

$$\begin{bmatrix}1\\0\end{bmatrix} \xrightarrow{\text{Rabi flop}} \begin{bmatrix}\sqrt{1-a}\\ \sqrt{a}\end{bmatrix} \xrightarrow{\text{Free evolution}} \begin{bmatrix}\sqrt{1-a}\\ \sqrt{a}e^{i\delta}\end{bmatrix}$$

If the free evolution is non-linear a la Weinberg, δ **depends on a**, a feature that is **qualitatively distinct** from any linear quantum mechanical evolution.

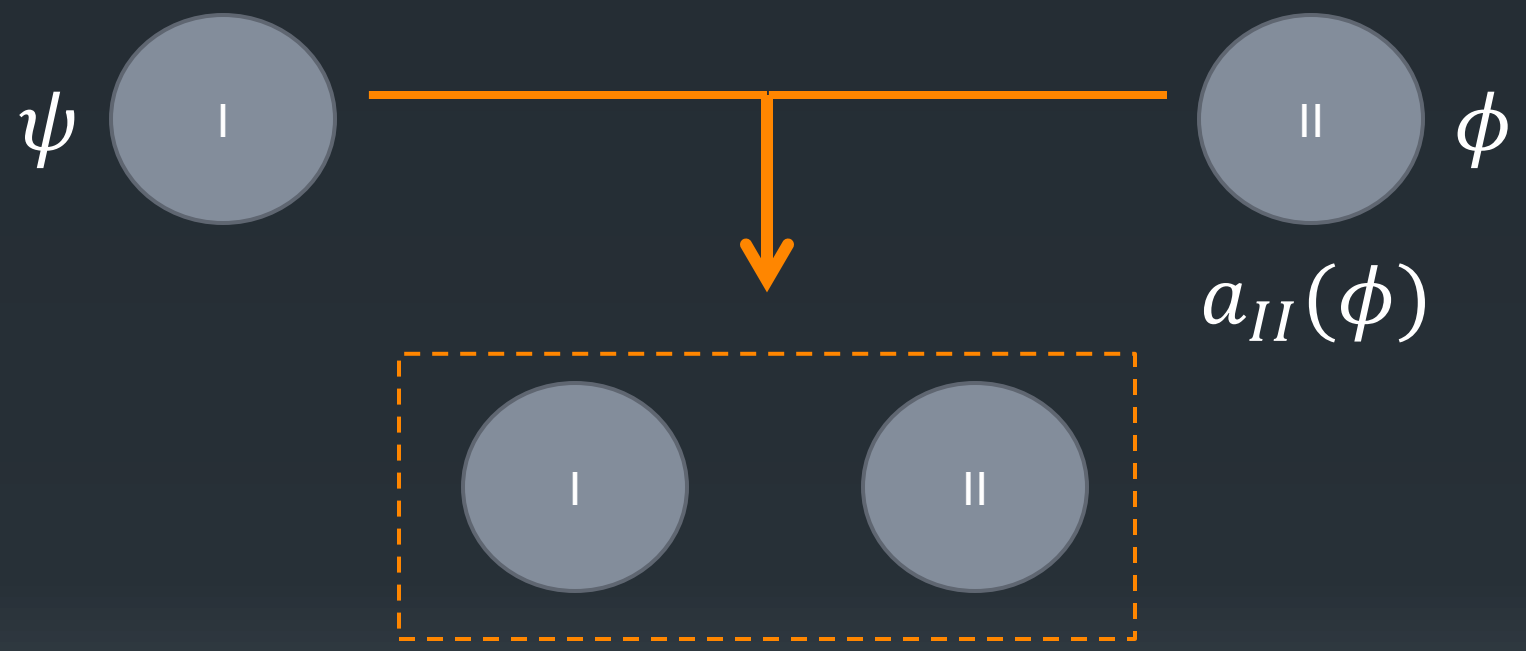
Experiment by Bollinger *et al**

- Used a hyperfine nuclear transition of $^{9}Be^{+}$
- Model non-linearity: $2\varepsilon a^2$
- Set a limit:

$$\varepsilon \leq 8 \pm 16 \cdot 10^{-21} eV$$

*Physical Review Letters 63, 1031 (1989)

Nonlinearity and Nonlocality



$$a_{II}^{\otimes}(\psi \otimes \phi) = ???$$

Non-locality

- How can we combine separated systems?
- Weinberg proposes a form that permits separable solutions
- However, this form is basis-dependent
- Polchinski has proven that it permits instantaneous communication

Polchinski and Kibble

Can we get logical consistency?

Remove nonlocality: Polchinski's proposal*

- Basis-independent solution: reduced density matrices
- Eliminates nonlocality, but causes communication between wavefunction branches
  - Binary messages of arbitrary length can be exchanged between the same observer in parallel worlds(!)
- In practice, wavefunction-branch coupling might be so complex that effects would be unobservable

*Physical Review Letters 66, 397 (1991)

Wavefunction Branch Communication

Observer + two-state system

↓

Observe spin

+1/2 ↙ ↘ -1/2

Nonlinear time evolution

↓

Observe spin again--outcome depends on choice of A or B!

Choose action A or B

"Many Worlds" interpretation seems natural—
But is this consistent?

Kibble's Nonlinear QFT*

- Start in Schrödinger picture, introduce nonlinearity by allowing the Hamiltonian to depend on the wavefunction:

$$i\frac{d}{dt}|\psi\rangle = H_\psi|\psi\rangle$$

- Preserve locality: write Hamiltonian as an integral over a density:

$$H_\psi = \int \begin{bmatrix} \frac{1}{2}\pi^2 + \frac{1}{2}\left(\vec{\nabla}\phi\right)^2 + \frac{m}{2}\phi^2 + \frac{g}{4!}\phi^4 \\ +\alpha + \beta\langle:\phi^2:\rangle_\psi + \frac{\lambda}{2}\langle:\phi^2:\rangle_\psi\phi^2 \end{bmatrix} d^3x$$

*Commun. Math. Phys. 64, 73-82 (1978)

Physical Consequences (g=0)

$$\omega_{\vec{k}}^2 = \left|\vec{k}\right|^2 + m^2 + \lambda\langle:\phi^2(\vec{x}):\rangle_\psi$$

- Effects will be strongest for localized wavefunctions
- Wavepackets will show anomalous dispersion
- Scattering can occur even in the absence of interactions
  - No “free” theory, really

Generic Difficulties for NLQM

- Perturbation theory difficult
  - Can’t get to a Heisenberg or interaction picture easily
- Consistent probabilistic interpretation challenging
  - Scattering not a well-posed question
- **Basic logical consistency is uncertain**

Conclusions

Questioning Quantum Mechanics?

- Can Quantum Mechanics from non-linear dynamics?
  - Concrete example: Weinberg's framework.
- Are there observable consequences of a fundamentally new character?
  - Yes; state-dependent phases, nonlocality, parallel universe communication
- Can a nonlinear theory be logically consistent?
  - Remove nonlocality? (Polchinski, Kibble)
  - Fundamental challenges

The End! Thanks for listening!

Another consequence of non-linear quantum mechanics?

Details of New Phase

$$n \equiv |\psi_1|^2 + |\psi_2|^2 \qquad a \equiv \frac{|\psi_2|^2}{n}$$ (definitions)

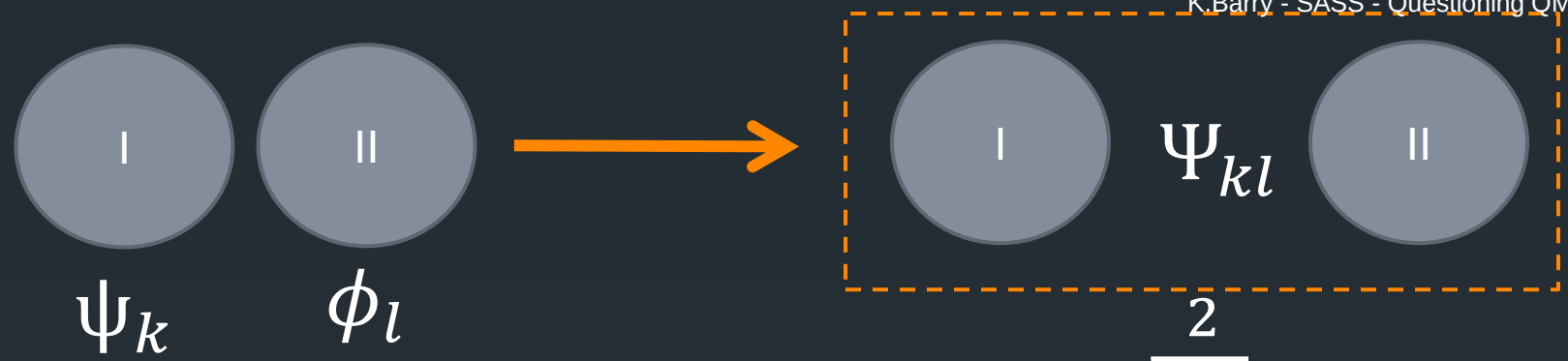
Model Hamiltonian function:

$$h(\psi^*, \psi) = n[(1-a)E_1 + aE_2 + 2\varepsilon a^2]$$

Phase difference between the two components after a time t:

$$\delta = t[E_1 - E_2 - 4\varepsilon a]$$

Nonlinearity and Nonlocality



$$a_{II} = |\phi_1|^4$$

$$a_{II}^{\otimes} = \sum_{k=1}^{2} |\Psi_{k1}|^4$$

$$|\Psi\rangle = |\psi_1\rangle \otimes |\phi_1\rangle \longrightarrow |\Psi\rangle = \left(\sqrt{1-\varepsilon^2}|\psi_1\rangle + \varepsilon|\psi_2\rangle\right) \otimes |\phi_1\rangle$$

$$a_{II}^{\otimes} = 1 \qquad a_{II}^{\otimes} = 1 - 2\varepsilon^2 + 2\varepsilon^4$$