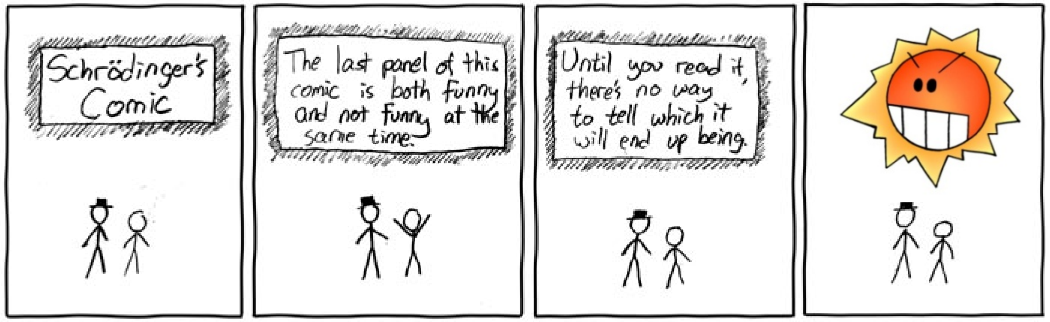
量子测量问题与量子力学诠释

孙昌璞

中国科学院理论物理研究所



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量子力学的理论框架

波动力学

薛定谔方程

$$i\hbar \frac{d}{dt}\psi(x,t) = H\psi(x,t)$$

波函数

$$|\psi(x,t)|^2$$

=发现粒子的几率密度

矩阵力学

可观测的光谱现象必须和两个“轨道”有关，必须用两个指标描述力学量

$$P_{mn},\quad Q_{mn} \quad \rightarrow \text{矩阵}\begin{bmatrix} x & x & .. \\ x & x & .. \\ .. & .. & .. \end{bmatrix}$$

$$[Q,\ P] \neq 0$$

$$\boxed{\Delta Q\ \Delta P\ \square\ \hbar}$$

承上启下的第五次Solvay 会议(1927)

“Electrons and photons”

Quantum Theory – “Quantum Wave Mechanics” - takes flight

量子力学诠释

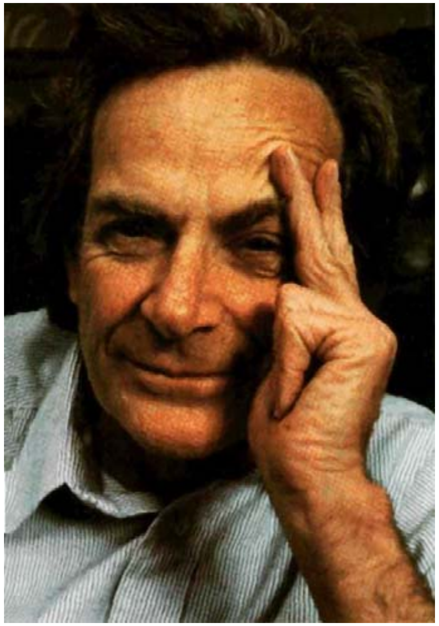
Interpretation of quantum mechanics

A statement which attempts to explain how quantum mechanics informs our understanding of nature

量子力学诠释旨在给出量子力学理论的 实验含义，本质在于揭示量子力学是怎样精确表达了微观世界的运作方式。虽然量子力学是科学史中经过多次检验的最精准的理论，但其理论的基础却尚未被完整被理解。目前有一些思想学派彼此竞争，其差异点在于量子力学是否最终可以被理解为决定性的**(deterministic)**、量子力学中哪些要素可以被视为“真实”**("real")**的**.**

量子力学需要诠释吗?

Quantum Mechanics
needs Interpretation or Not?



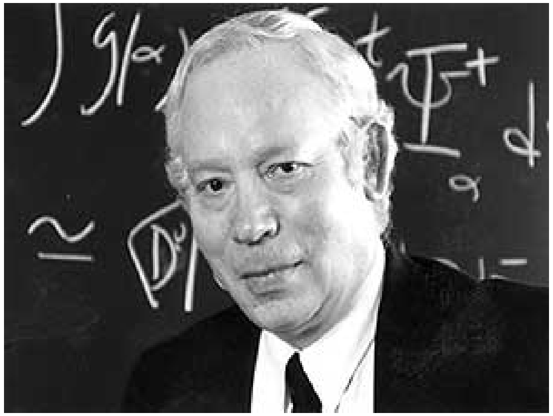
工具主义 (**Instrumentalist**)的观点:

Shut up and calculate !!
—Richard Feynman.

N. David Mermin, Physics Today , May 2004, p. 10

不同的观点！

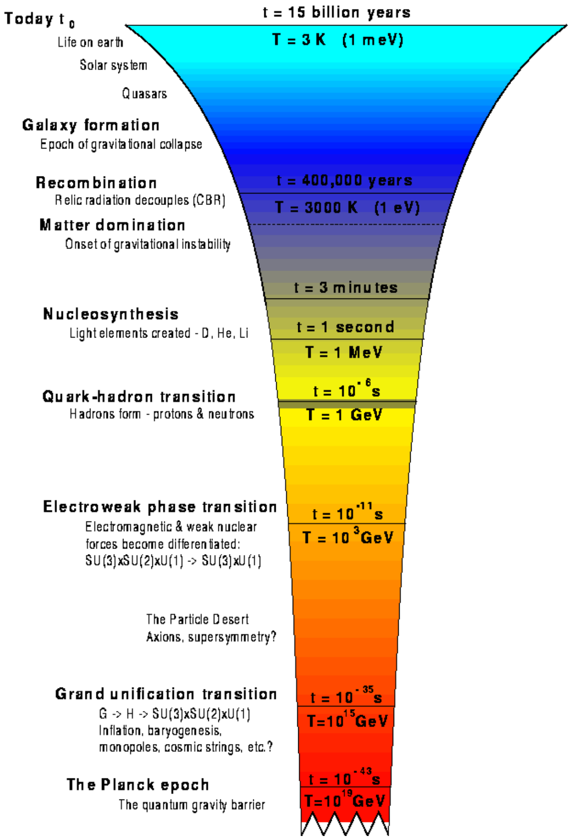
Steven Weinberg in "Einstein's Mistakes", *Physics Today*, 2005



“Bohr's version of quantum mechanics was deeply flawed, but not for the reason Einstein thought. The Copenhagen interpretation describes what happens when an observer makes a measurement, but the observer and the act of measurement are themselves treated classically.

This is surely wrong: Physicists and their apparatus must be governed by the same quantum mechanical rules that govern everything else in the universe. But these rules are expressed in terms of a wave function (or, more precisely, a state vector) that evolves in a perfectly deterministic way. So where do the probabilistic rules of the Copenhagen interpretation come from?”

Steven Weinberg in "Einstein's Mistakes", *Physics Today*, 2005

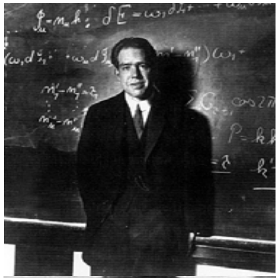


Considerable progress has been made in recent years toward the resolution of the problem,…… It is enough to say that neither Bohr nor Einstein had focused on the real problem with quantum mechanics. The Copenhagen rules clearly work, so they have to be accepted. But this leaves the task of explaining them by applying the deterministic equation for the evolution of the wave function, the Schrödinger equation, to observers and their apparatus.

The problem of thinking in terms of classical measurements of a quantum system becomes particularly acute in the field of quantum cosmology, where the quantum system is the universe

哥本哈根诠释

Asher Peres Book



1. A system is completely described by a wave function ψ, which represents an observer's knowledge of the system. (Heisenberg)

2. The description of nature is essentially probabilistic. The probability of an event is related to the square of the amplitude of the wave function related to it. (Max Born)

3.Heisenberg's uncertainty principle states the observed fact that it is not possible to know the values of all of the properties of the system at the same time; those properties that are not known with precision must be described by probabilities.

4.Complementarity principle: matter exhibits a wave-particle duality. An experiment can show the particle-like properties of matter, or wave-like properties, but not both at the same time.(Niels Bohr)

5.Measuring devices are essentially classical devices, and measure classical properties such as position and momentum.

6.The correspondence principle of Bohr and Heisenberg: the quantum mechanical description of large systems should closely approximate to the classical description.

量子测量假设-量子力学诠释之一

被测量系统处于量子态

$$|\psi\rangle = \sum_n c_n |n\rangle$$

$$(A|n\rangle = a_n |n\rangle)$$

测量力学量**A**一次,得到结果 a_n

$$|\psi\rangle = \sum_n c_n |n\rangle \to |n\rangle$$

The Chinese Academy of Science

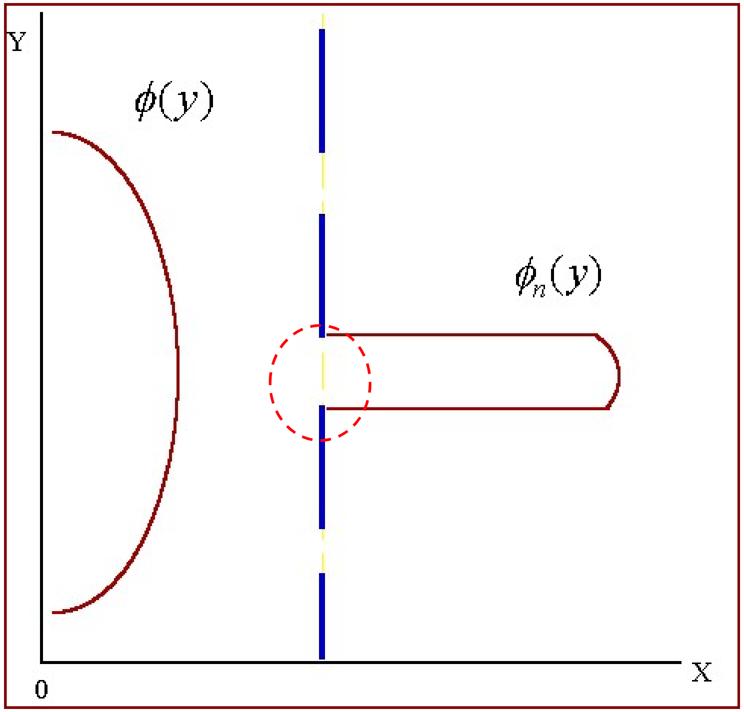
量子测量的单粒子图象及其困境

例子, sieve 测量位置

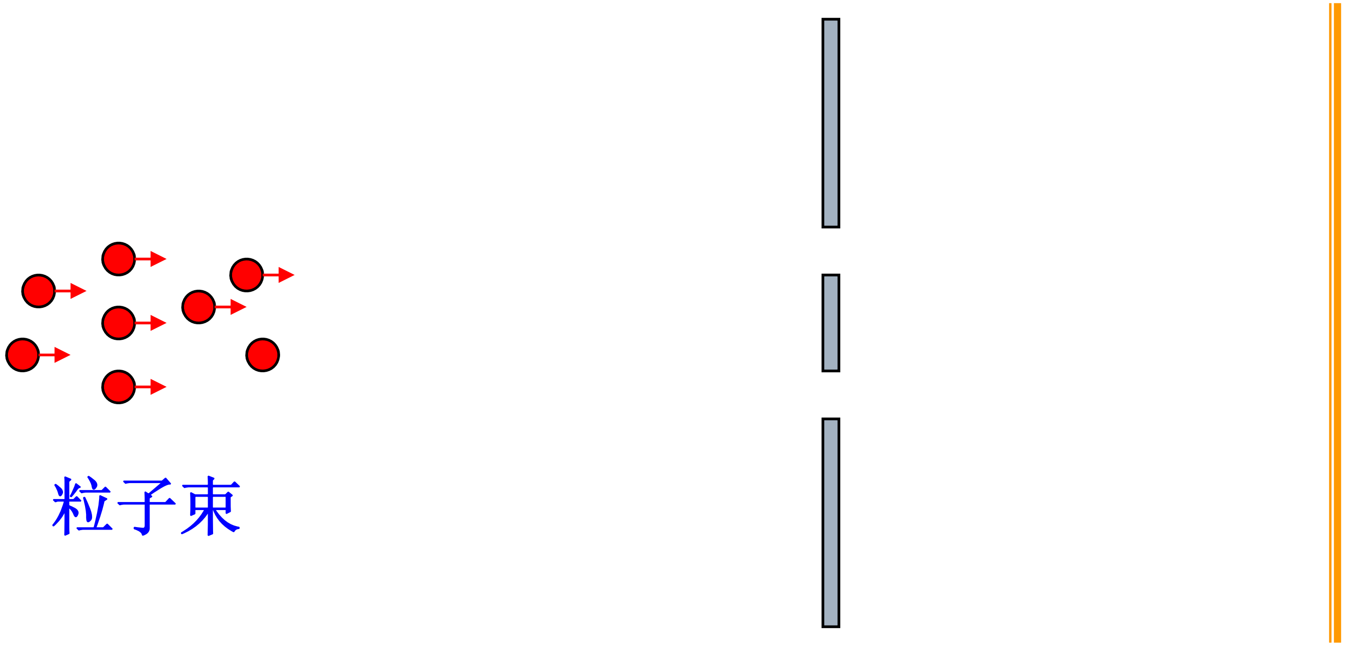
$$\phi(y) = \langle y | \psi \rangle$$

$$\phi_n(y) = \begin{cases} N_n \phi(y), & na \le y < (n+1)a \\ 0, & na \ge y \ or \ \ge (n+1)a \end{cases}$$

$$N^{-1}{}_n = \sqrt{\int_{na}^{(n+1)a} |\psi(y)|^2 \, dy}$$



波粒二象性

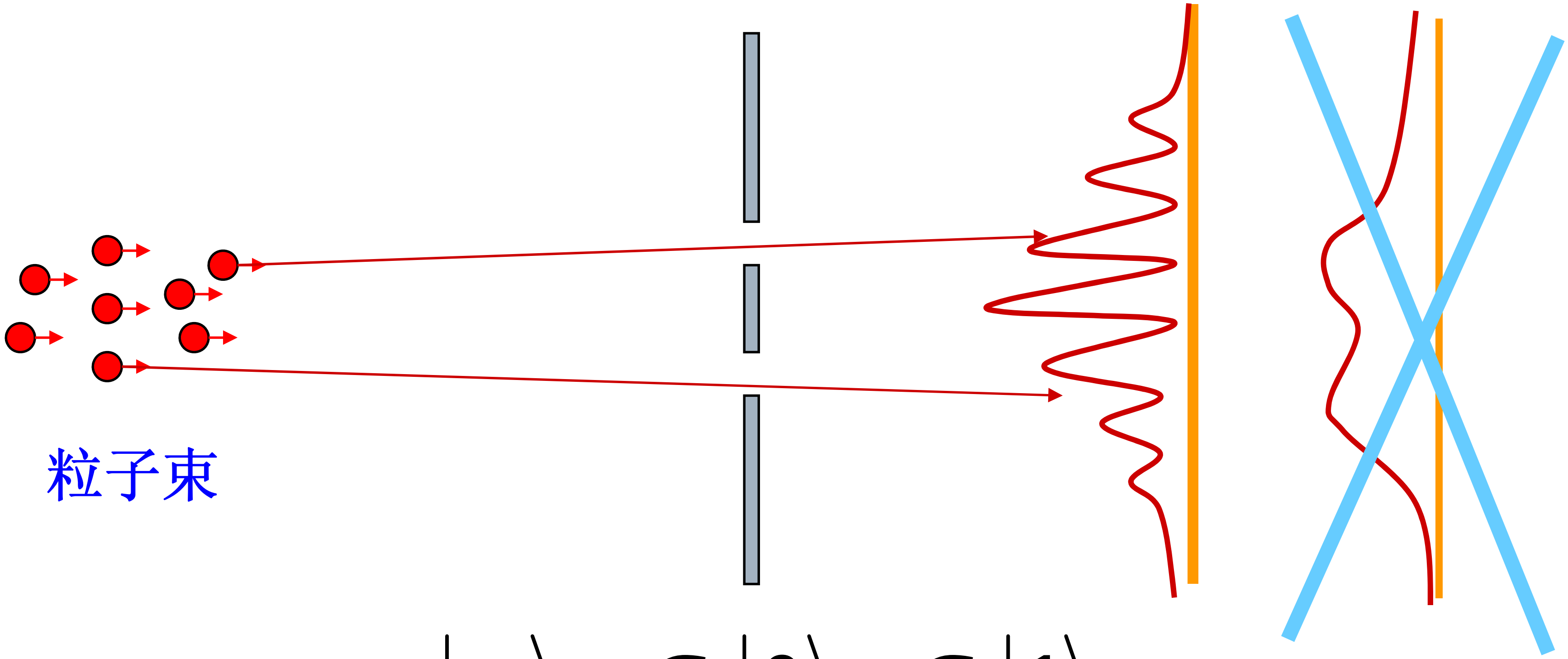


粒子束

粒子探测器

粒子的双缝实验

波粒二象性

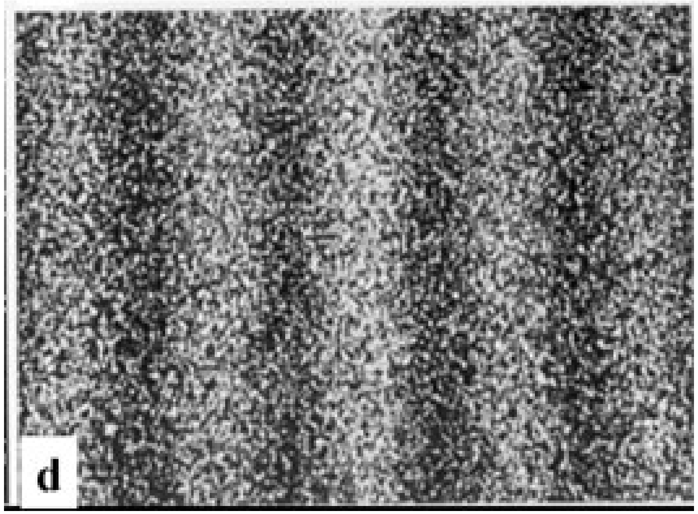


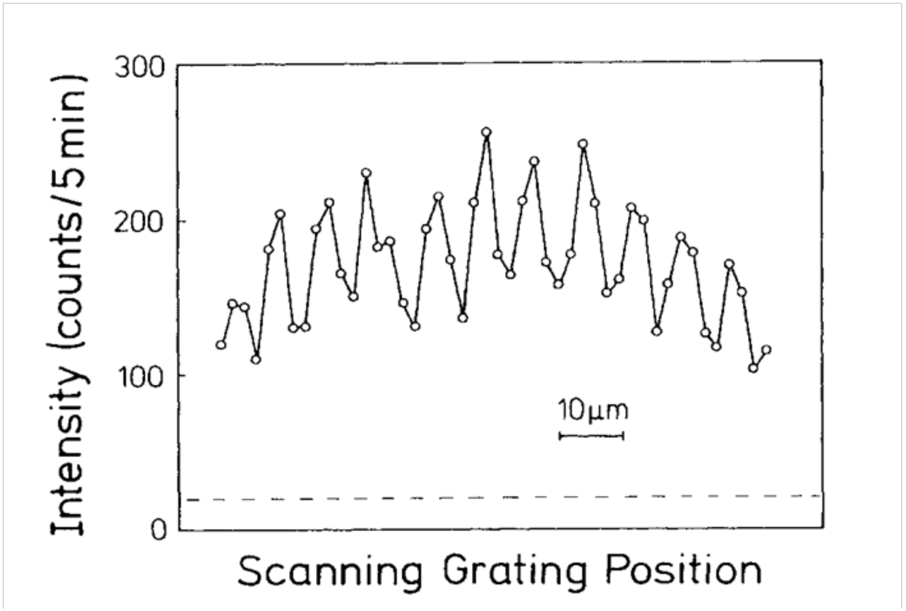
$$|\psi\rangle = C_0|0\rangle + C_1|1\rangle$$

实际粒子的双缝实验

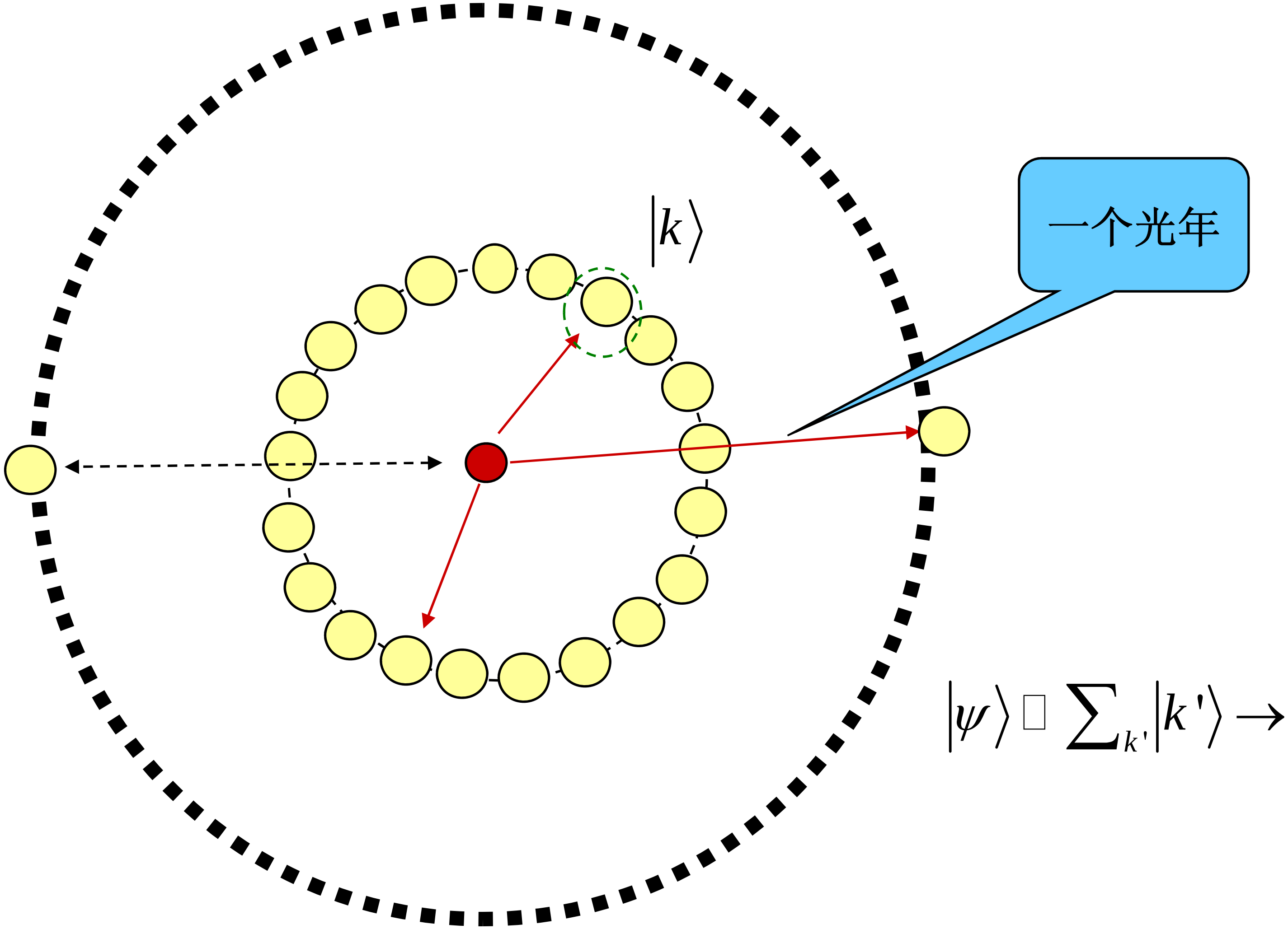
电子

原子



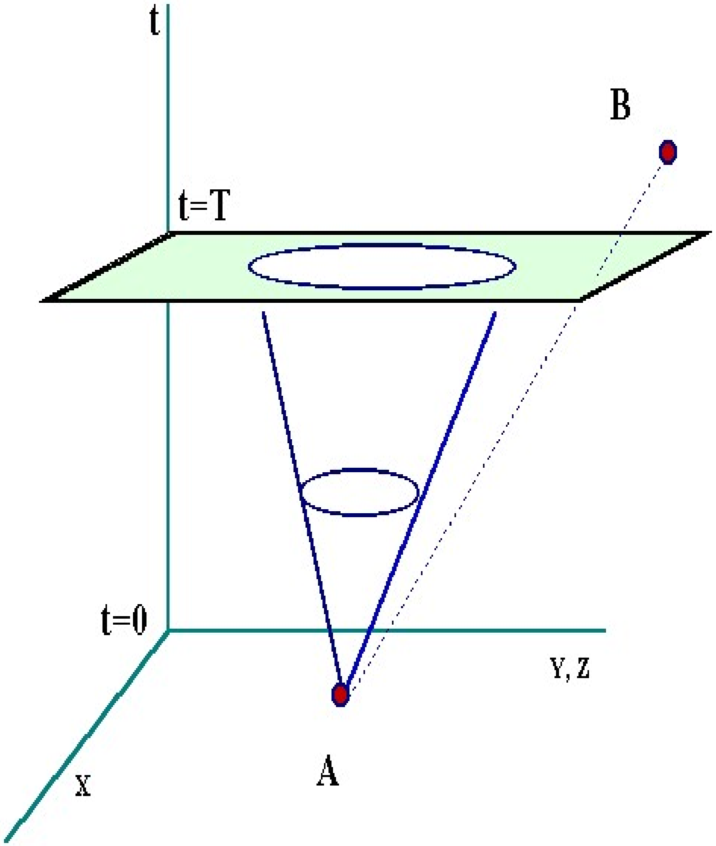


波包塌缩：爱因斯坦“光子球”



$$|\psi\rangle \square \sum_{k'} |k'\rangle \rightarrow |k\rangle$$

与狭义相对的矛盾?

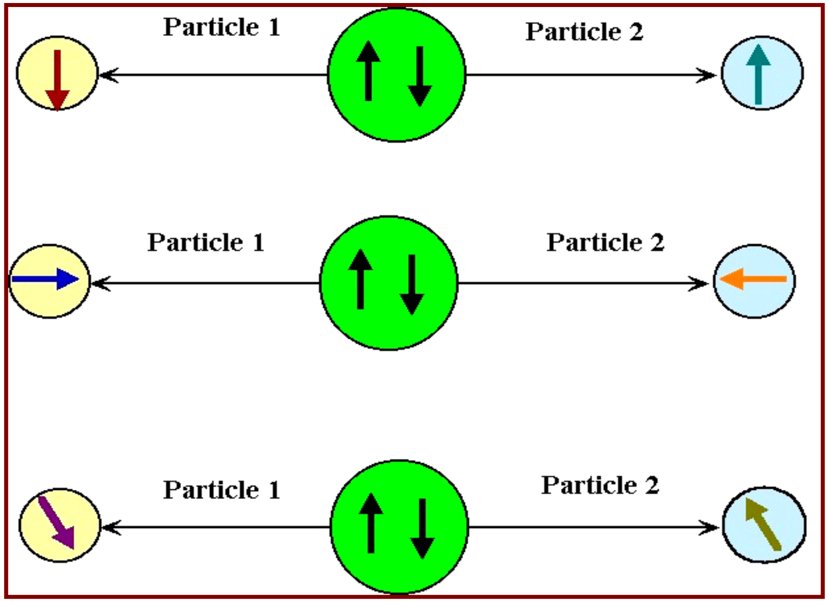


对定域在A 的粒子测量动量，塌缩到平面 波|K>上，只可以以一定的概率，在与A 类空的B发现粒子.

不存在通常意义下的超光速和因果关系破坏。目前对一些误称为“超光速”的现象的认识模糊均在于此.

$$\varphi(x,0)=\delta(x-a)\Box\sum\exp(ikx)$$

量子纠缠与EPR佯谬



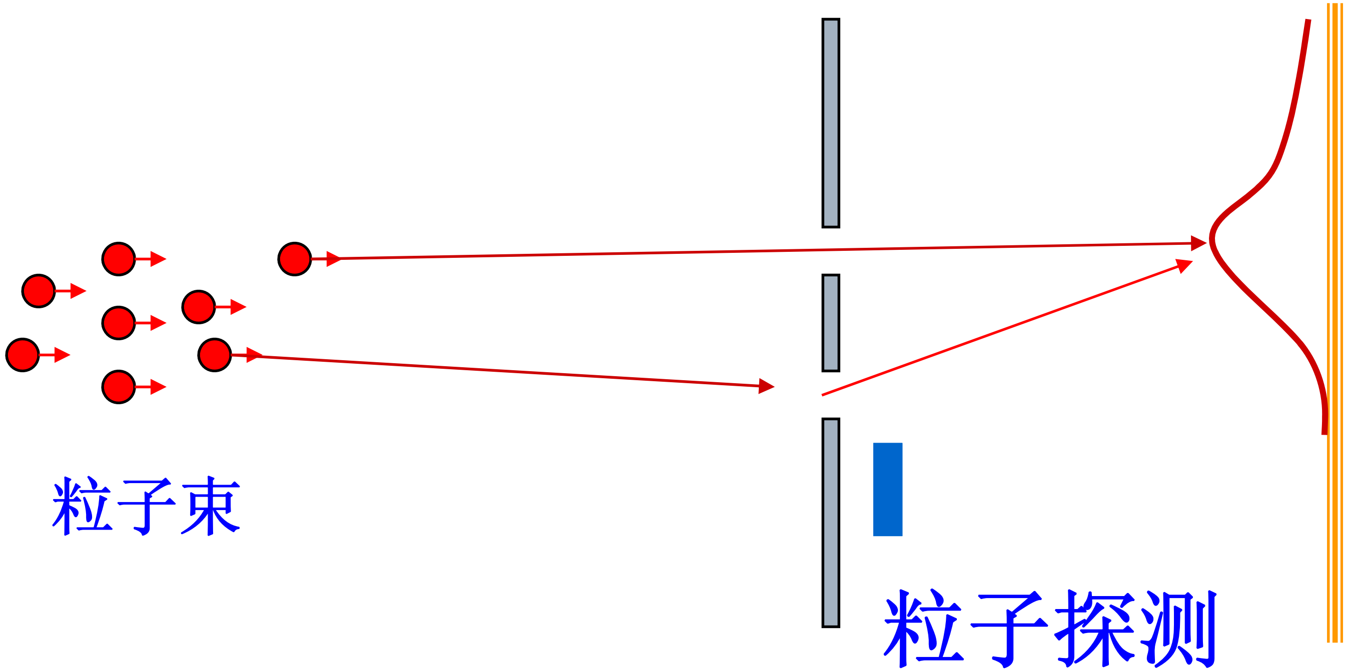
$$\begin{aligned}\left|EPR\right\rangle &= \tfrac{1}{\sqrt{2}}\left[\left|\uparrow,\downarrow\right\rangle - \left|\downarrow,\uparrow\right\rangle\right]\\ &= \tfrac{1}{\sqrt{2}}\left[\left|+,-\right\rangle - \left|-,+\right\rangle\right]\\ &= \tfrac{1}{\sqrt{2}}\left[\left|\vec{n},-\vec{n}\right\rangle - \left|-\vec{n},\vec{n}\right\rangle\right]\end{aligned}$$

SO(3)不变性

当事先没有约定自旋测量的方向(测量基矢), 就没有通常的关联, 因此也无超光速通讯！ 基矢约定需要传递经典信息, 详细分析需要**Bell** 不等式.

量子退相干诠释

Decoherence



粒子束

粒子探测

波包塌缩

Wave Packet Collapse (WPC)

量子测量的系综图象

量子几率到经典几率的转换

$$\rho = |\psi\rangle\langle\psi| = \sum_n c^*_m c_n |n\rangle\langle m| \to \rho_M = \sum_n |c_n|^2 |n\rangle\langle n|$$

测量导致密度矩阵非对角项消失

$$\langle x|\psi\rangle = \sum_n c_n \phi_n(x) = c_1\phi_1(x) + c_2\phi_2(x)$$

$$\rho(x,x) = |c_1|^2 |\phi_1(x)|^2 + |c_2|^2 |\phi_2(x)|^2 + \underbrace{c^*_1 c_2 \phi^*_1(x)\phi_2(x) + c.c.}_{\text{干涉条纹：}}$$

随机位相解释量子退相干

Heisenberg, 1927

测量前 $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$

测量后随机位相引入,导致量子退相干

$$|\psi'\rangle = \alpha|0\rangle + \beta e^{i\phi\theta}|1\rangle$$

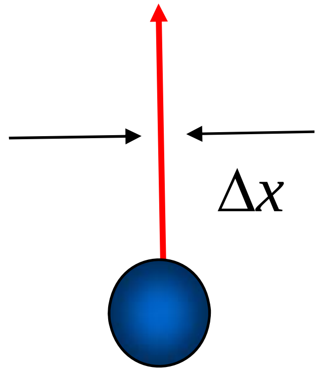
$$\left(|\psi'\rangle\langle\psi'|\right)_{\text{平均?}} = |\alpha|^2|0\rangle\langle 0| + |\beta|^2|1\rangle\langle 1| + \alpha^*\beta|0\rangle\langle 1|\underset{\overset{\|}{0}}{\left(e^{i\theta}\right)_{\text{平均}}} + h.c.$$

量子力学互补原理解释

物质具有波动粒子二重属性,但在同一个实验中二者互相排斥

直观解释：不确定性原理

$$p = \hbar k + \Delta p$$



$$\Delta x \square \Delta p \sim \hbar$$

粒子性

波动性

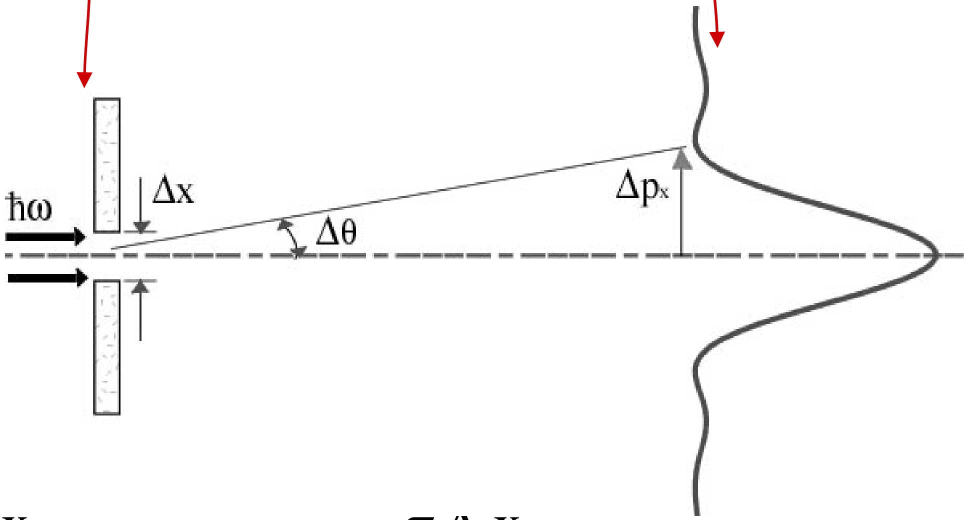
“粒子在测量中产生” ⇒ “粒子属性在位置测量中产生”

Bohr-Einstein 的争论， 1927-1931

动量测量

$$\Delta p_x \cdot \Delta x \geq h$$

位置测量

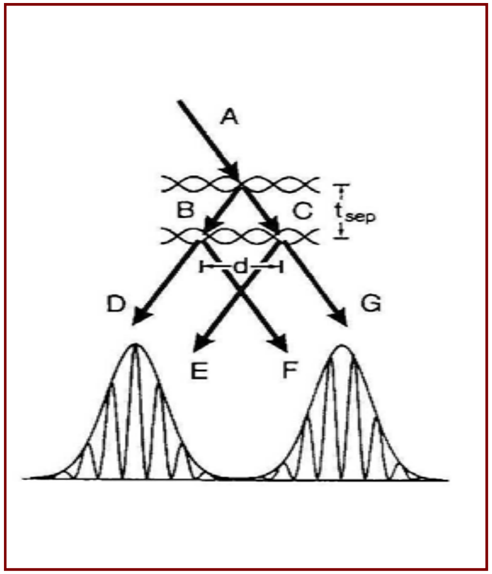


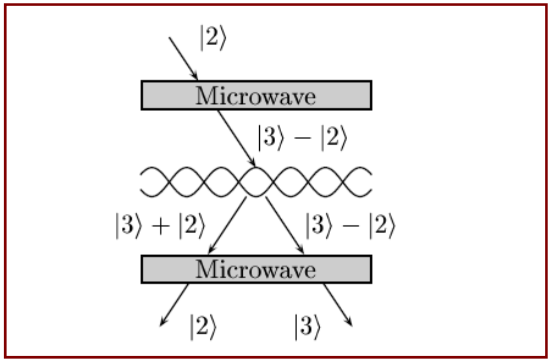
$$\operatorname{sinc}\frac{\pi\,\Delta\,x}{\lambda}\Delta\theta = 0 \quad\Rightarrow\quad \frac{\pi\,\Delta\,x}{\lambda}\Delta\theta = \pi \quad\Rightarrow\quad \Delta\theta = \frac{\lambda}{\Delta\,x}$$

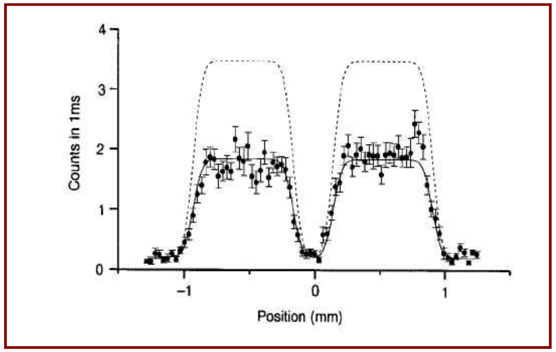
$$\Delta p_x \cong \frac{h}{\lambda}\Delta\theta = \frac{h}{\lambda}\frac{\lambda}{\Delta\,x} = \frac{h}{\Delta\,x} \quad\Rightarrow\quad \therefore\ \Delta\mathbf{p}_{\mathbf{x}} \cdot \Delta\mathbf{x} = \boldsymbol{h}$$

动量微扰是否是干涉条纹消失的原因?

实验：　　Nature, 395,33(1998)







不可控动量扰动不是退相干的唯一原因

量子纠缠：在相互作用中产生,广义的测不准原理

波包塌缩，虚构或现实？

波包塌缩（WPC） $|\psi\rangle = \sum C_n |n\rangle \longrightarrow |n\rangle$

$$A|n\rangle = a_n |n\rangle$$

“紧接着A的第二次测量得到相同结果”

退相干（Decoherence） $\rho = |\psi\rangle\langle\psi| \longrightarrow \rho_d = \sum |C_m|^2 |m\rangle\langle m|$

第二类波包塌缩， 描述一个系综

第二次重复测A也得到相同结果

$$\overline{A} = Tr(\rho A) = Tr(\rho_d A)$$

Thank You !