面向前沿科技，探索研究型物理实验教学

北京大学物理学院 张朝晖

全国高等学校实验物理教学研究会第六届常务理事会2023年工作会议，7月19日-22日，井冈山

（一）联系前沿科技应用，深化基础物理实验课程的教学研究

迈克尔孙干涉仪 → 傅里叶变换光谱检测、光学干涉断层成像 → LIGO引力波测量

—— 探究物理实验的新技术

（二）探究前沿物理研究的新进展，开发基础物理实验教学的新实验

双光子量子纠缠实验 → 双光子量子干涉实验 → 量子隐形传态实验

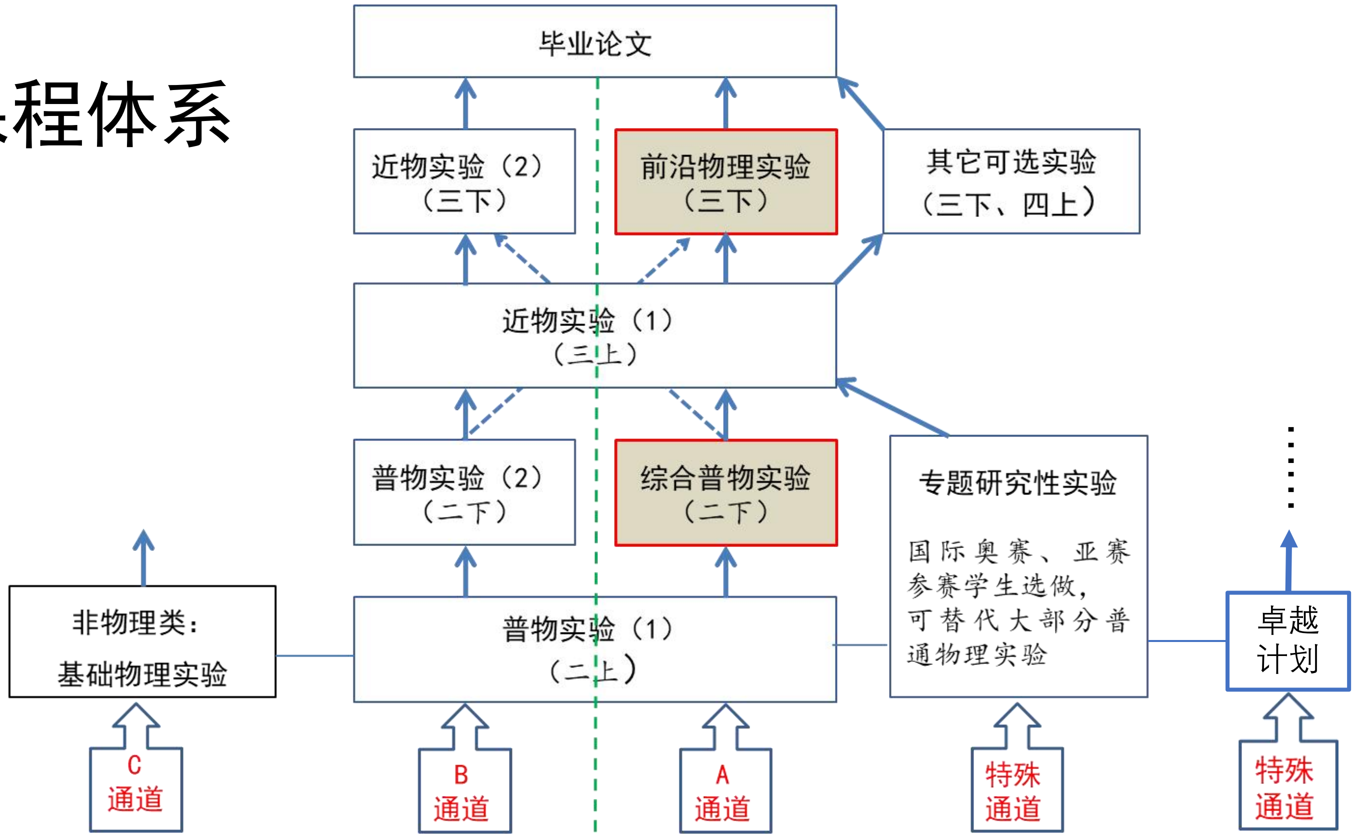
—— 探究量子力学的新进展

分层次、多种教学模式的课程体系

传统教学　　　　创新教学

平衡

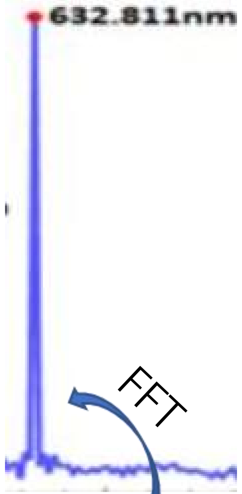
教学理念、教学模式、教学体系



迈克尔孙干涉仪 $\rightarrow \begin{cases} \text{傅里叶变换光谱检测} \\ \text{光学相干层析成像} \end{cases} \rightarrow LIGO$引力波测量

—— 探究物理实验的新技术

探究傅里叶变换光谱检测技术



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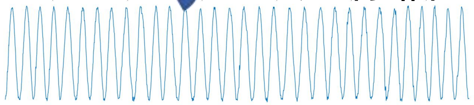

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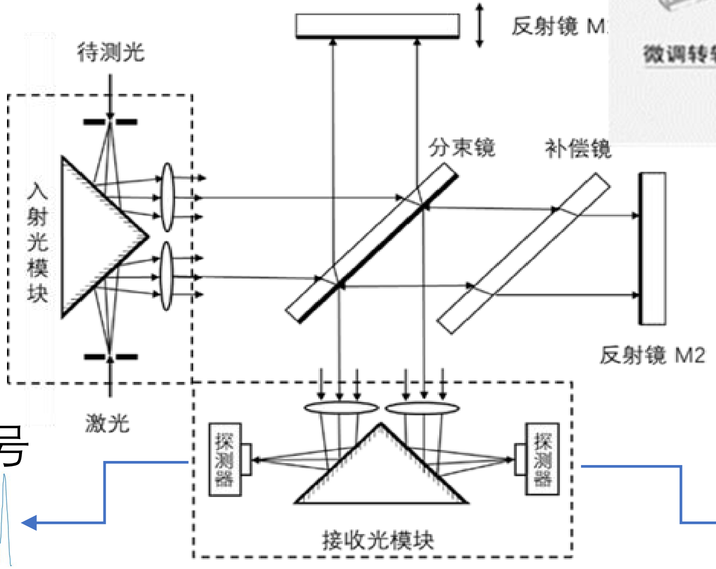


图10 傅里叶变换光谱测量的应用光路

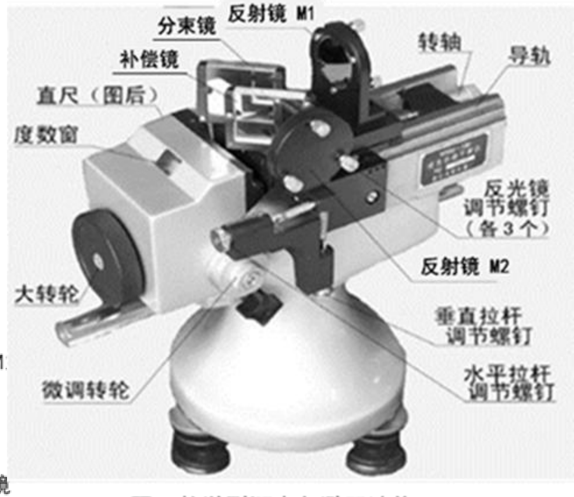
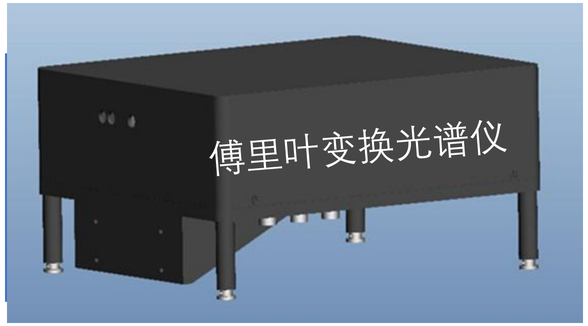
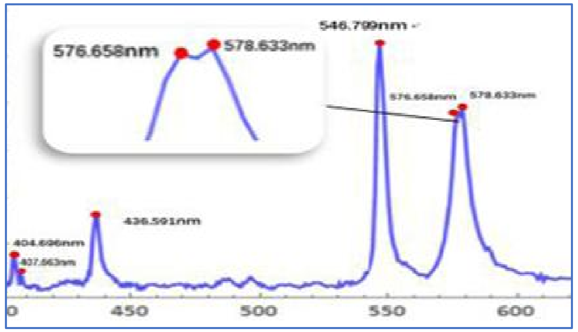


图2 教学型迈克尔逊干涉仪





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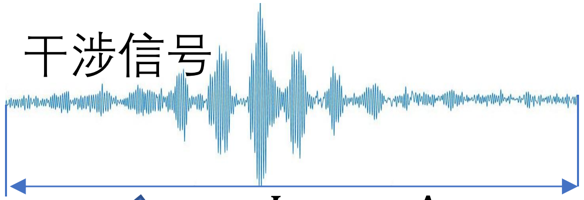
干涉信号



$L = n \cdot \Delta x$

采样定理：

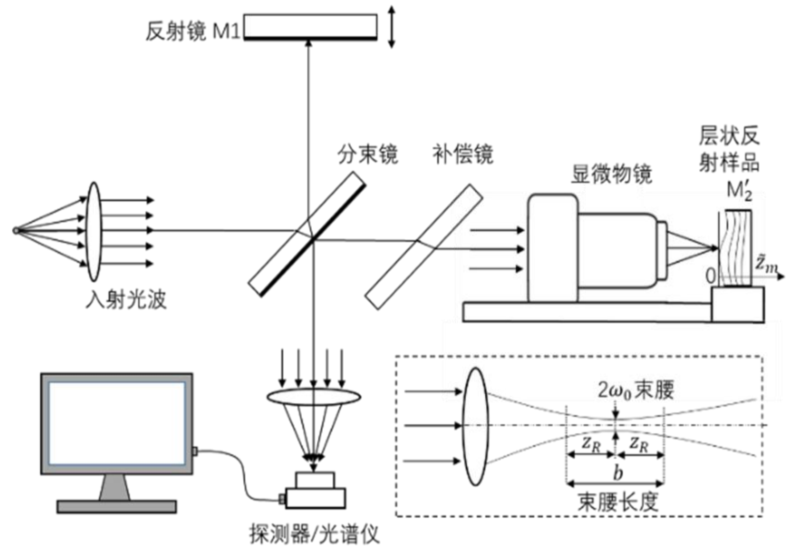
$$\Delta x \le \frac{1}{2k_{max}},$$

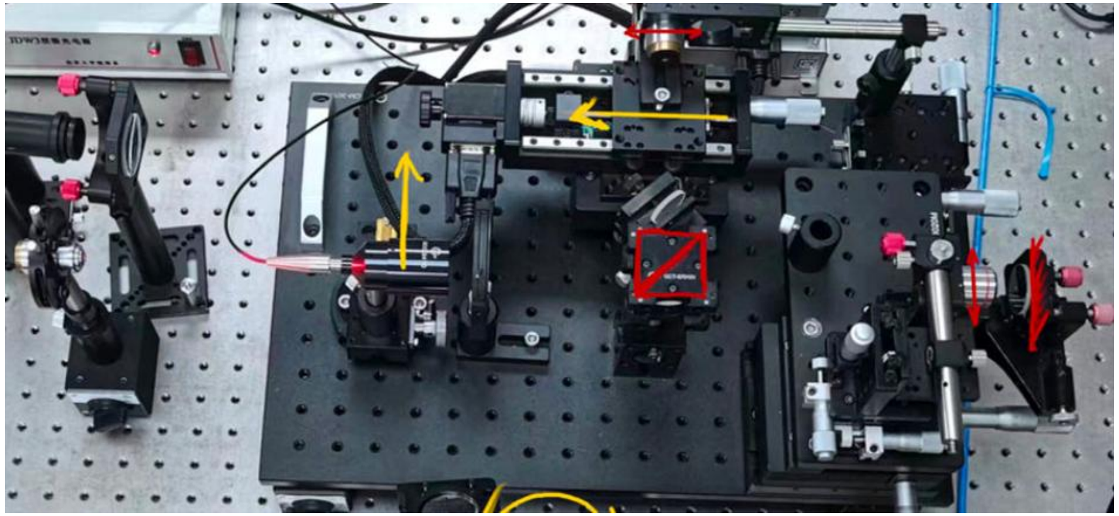
$$k_{max} = \frac{1}{\lambda_{min}},$$

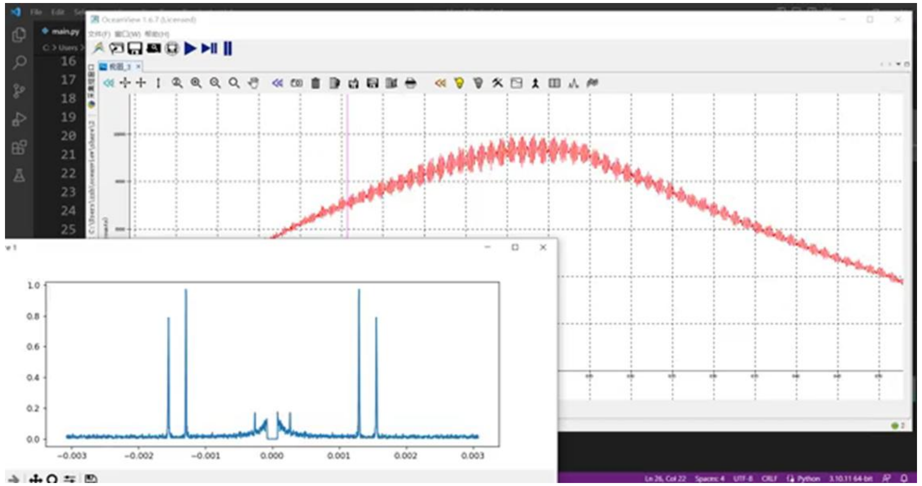
$$\Delta x \le \frac{\lambda_{min}}{2}.$$

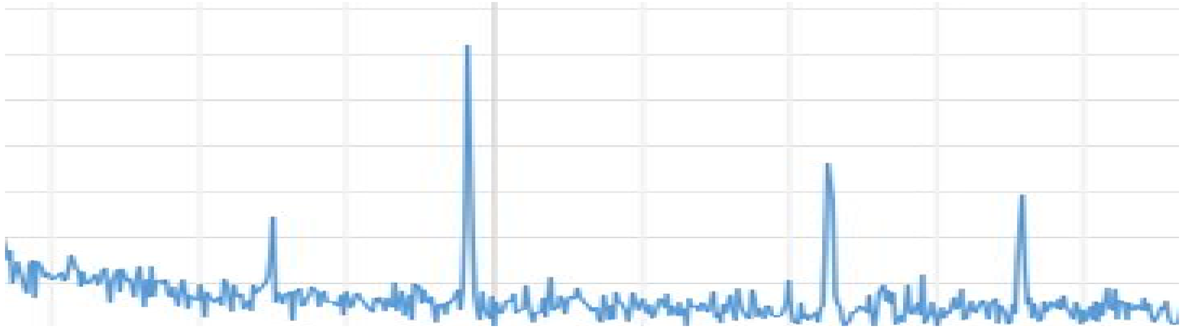
定标动镜M1的位移，
为干涉信号提供横坐标

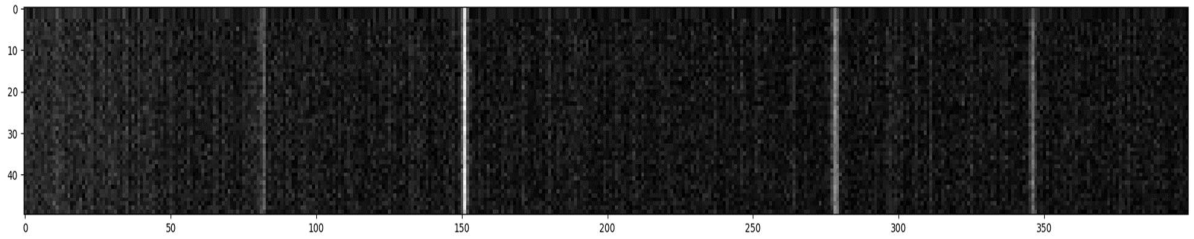
探究光学干涉断层成像技术





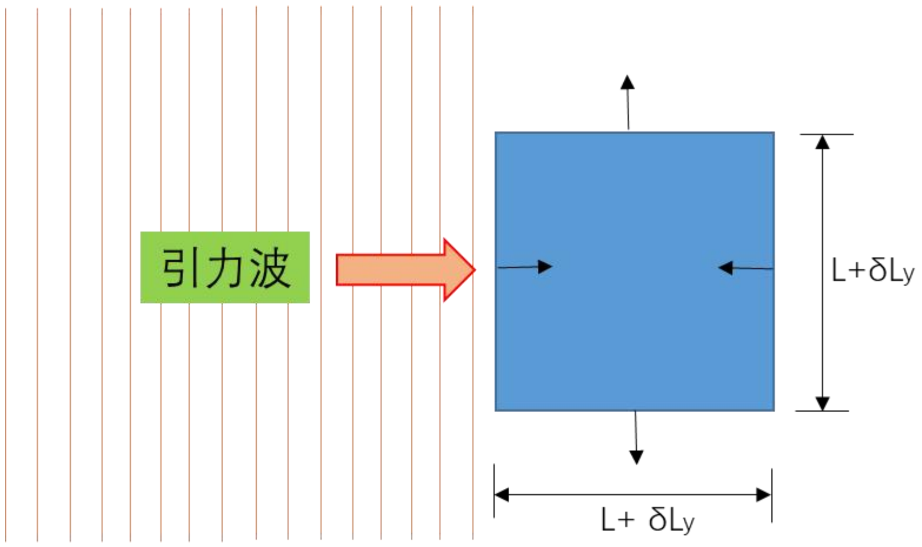






LIGO的迈克尔逊干涉仪：测量引力波引起的空间应变 $\varepsilon=1.0\times10^{-21}$

- 引力波应变是时空涟漪引起空间几何上的相对改变。在引力波经过干涉仪的过程中，空间在一个方向上收缩伴随与其垂直方向上延伸，反之亦然。
- 由胡克定律的相关实验知道，材料的应变定义为 $\varepsilon=\delta L/L$，是在一个维度上长度L的相对改变量。
- 由$\varepsilon=1.0\times10^{-21}$可知，要想如同迈克尔逊-莫雷实验预期那样测得0.4个条纹的变化，用迈克尔逊干涉仪测量引力波的臂长就得长达10^9 km，这长度超过了地球到太阳的距离（1.5×10^8 km），显然是无法做到的。



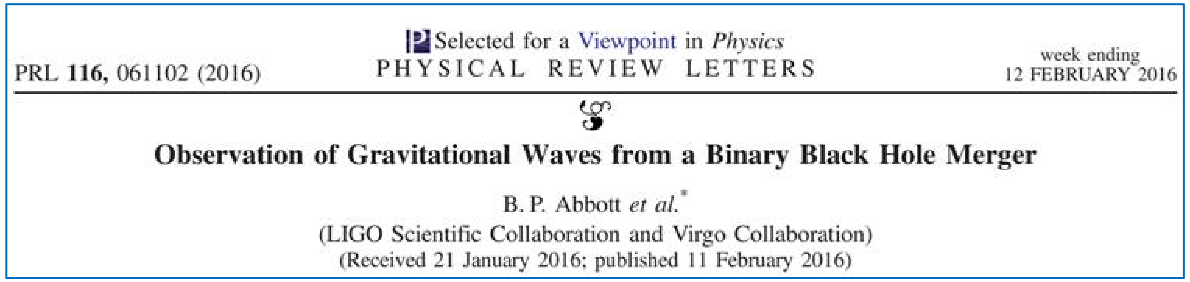
空间应变

$h(t)=(\delta L_x-\delta L_y)/L$

LIGO干涉仪的结构特征

- 正交的两臂各包含一个L=4km长的法布里－珀罗腔，两者在引力波中的腔长为Lx 和Ly。准直入射的 Nd:YAG 激光（波长：1064 nm）在其中经过b=300次反射后，形成光程差为z=2b(Lx-Ly)。
- 输入端的功率回收镜在整个干涉仪中提供了额外的激光共振增强，使得20W的激光输入增加到700W，入射到分束器上。

其中法布里－珀罗腔的作用与迈克尔逊-莫雷实验中置入多个反射镜类似，是为了更大限度地加大光程，放大极其微小的空间应变产生的光程差δz。同时，腔的长度L提供了一个测量空间应变h(t)的尺度，将δz与h(t)联系起来，即δz=2bLh(t),其中h(t)=(δLx-δLy)/L。


Selected for a Viewpoint in Physics
PRL 116, 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

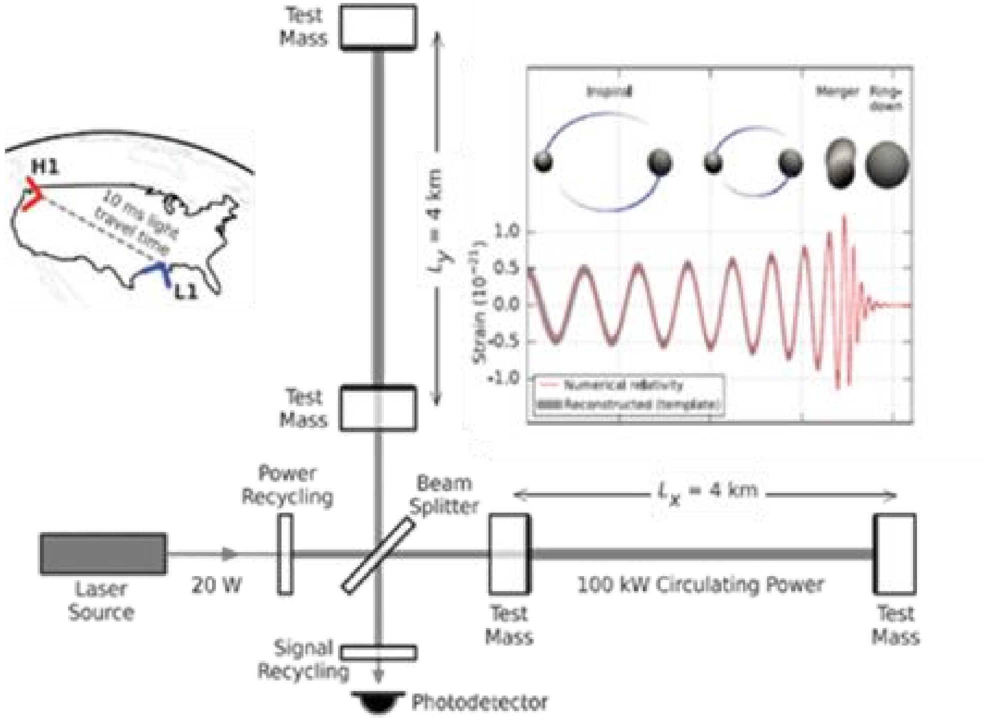


图8 LIGO 迈克尔逊干涉仪实验装置

LIGO干涉仪的光子计数测量

光的量子理论提供了强大的光子计数测量方法，建立起了干涉仪输出光子数N的概率分布与入射到干涉仪的光子数N_0的概率分布之间的统计关系，从而将光强测量转化为光子计数的统计测量：

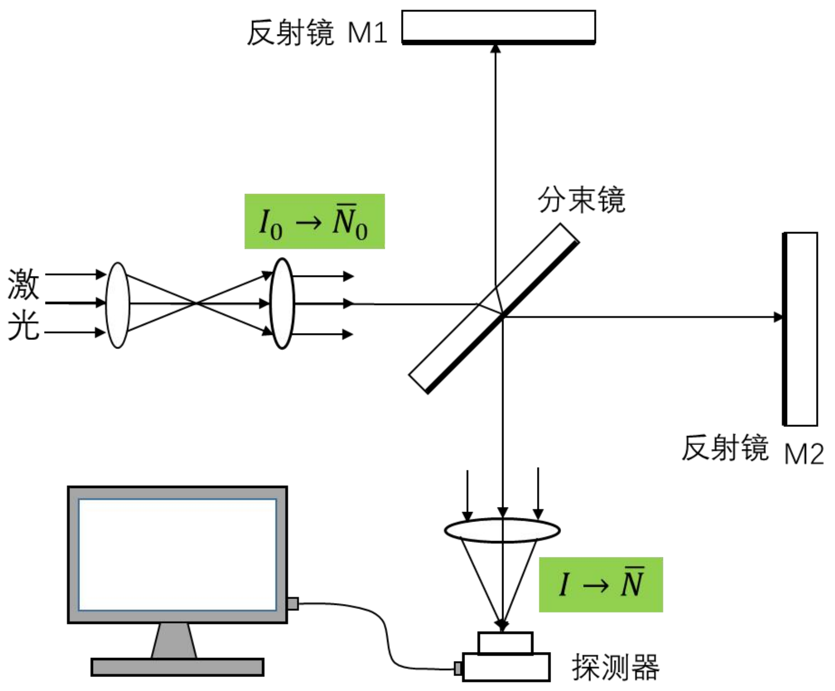
$$I(z) = I_0 sin^2\left(\frac{k_0 z}{2}\right) \Rightarrow \bar{N} = \bar{N}_0 sin^2\left(\frac{k_0 z}{2}\right)$$

并且输出光子数N的统计方差正好等于其均值$\bar{N}$，即 $\sigma = \sqrt{\bar{N}}$。

令 $\delta\bar{N} \geq \sqrt{\bar{N}}$，得到可以测量的空间应变为

$$h(t) \geq \frac{\lambda}{4\pi bLcos\left(\frac{k_0 z}{2}\right)\sqrt{\bar{N}_0}} \geq \frac{\lambda}{4\pi bL\sqrt{\bar{N}_0}} = \left(\frac{\lambda}{4\pi bL}\right)\sqrt{\frac{\hbar\omega}{TI_0}}$$

探测器积分时间T引力波的最高频率f_M应该满足采样定理，即$T \leq \frac{1}{2f_M}$



将 $f_M = 500$，$b = 300$，$L = 4 \times 10^3 m$，$I_0 = 700\ W$，$\lambda = 1064nm$ 代入

$$h_{min} = \left(\frac{\lambda}{4\pi bL}\right)\sqrt{\frac{\hbar\omega}{TI_0}}$$

得到 $h_{min} \approx 3.3 \times 10^{-23}$，即可测到空间应变在$10^{-21}$量级上的引力波。

双光子量子纠缠实验 → 双光子量子干涉实验 → 量子隐形传态实验

—— 探究量子力学的新进展

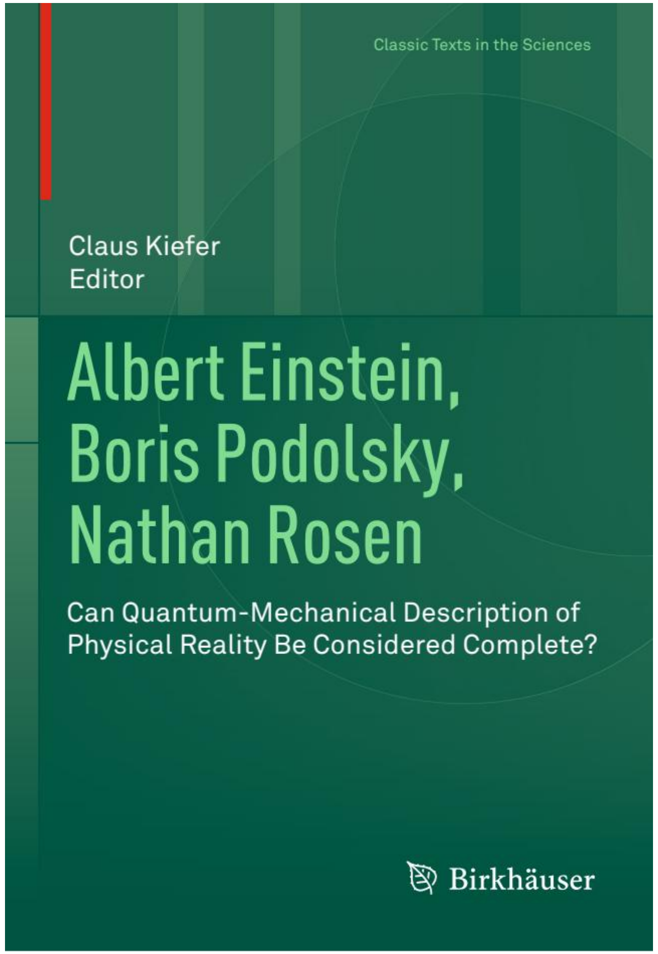
MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.



双光子量子纠缠实验

PHYSICAL REVIEW LETTERS

VOLUME 75 | 11 DECEMBER 1995 | NUMBER 24

New High-Intensity Source of Polarization-Entangled Photon Pairs

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Alexander V. Sergienko and Yanhua Shih
Department of Physics, University of Maryland Baltimore County, Baltimore, Maryland 21228
(Received 5 July 1995)

We report on a high-intensity source of polarization-entangled photon pairs with high momentum definition. Type-II noncollinear phase matching in parametric down conversion produces true

BBO晶体的高亮度双光子纠缠源

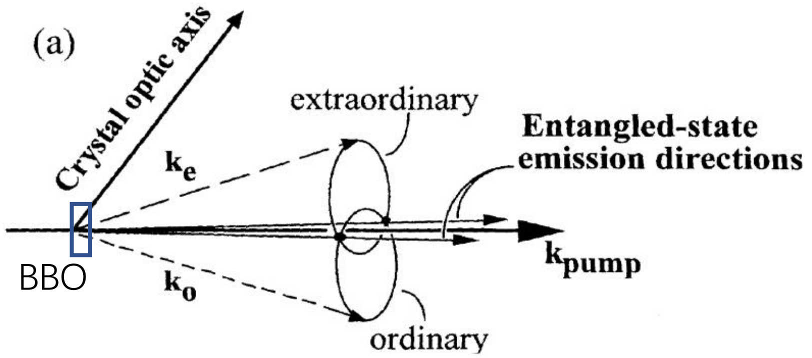

图 2: type-II SPDC 产生纠缠光子对过程示意图

Physics Vol. 1, No. 3, pp. 195–200, 1964 Physics Publishing Co. Printed in the United States

ON THE EINSTEIN PODOLSKY ROSEN PARADOX*

J. S. BELL†
Department of Physics, University of Wisconsin, Madison, Wisconsin

EPR佯谬和贝尔不等式

VOLUME 23, NUMBER 15 PHYSICAL REVIEW LETTERS 13 OCTOBER 1969

PROPOSED EXPERIMENT TO TEST LOCAL HIDDEN-VARIABLE THEORIES*

John F. Clauser†
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and

Michael A. Horne
Department of Physics, Boston University, Boston, Massachusetts 02215

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Abner Shimony
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and

Richard A. Holt
Department of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 4 August 1969)

CHSH不等式

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*
(Received March 25, 1935)

In a co[…] two to each el[…]ation reality of a[…]ystem it with c[…] that quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in […] had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

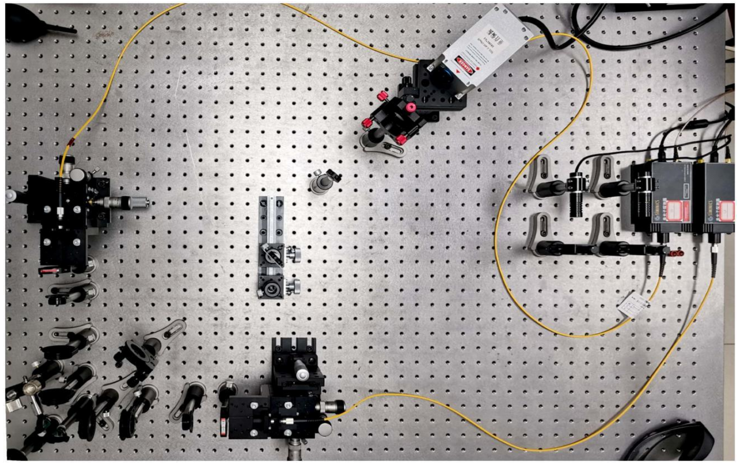
Einstein-Podolsky-Rosen论文

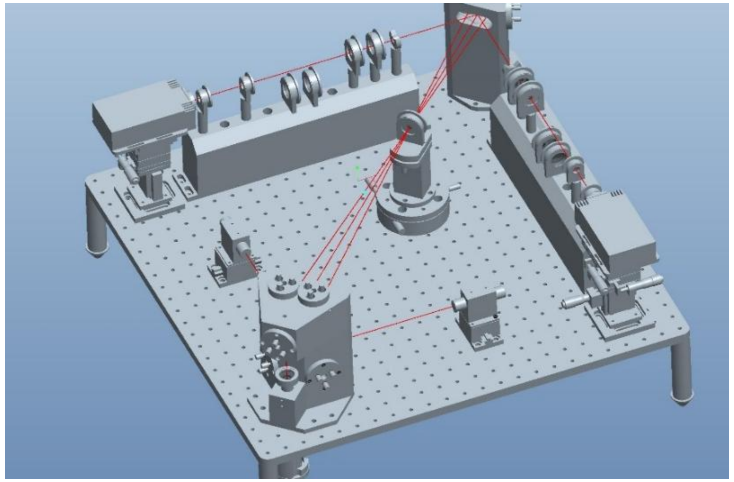
实验证伪贝尔不等式

$$E(\theta_1,\theta_2)=\frac{N(\theta_1,\theta_2)+N(\theta_1+\pi/2,\theta_2+\pi/2)-N(\theta_1+\pi/2,\theta_2)-N(\theta_1,\theta_2+\pi/2)}{N(\theta_1,\theta_2)+N(\theta_1+\pi/2,\theta_2+\pi/2)+N(\theta_1+\pi/2,\theta_2)+N(\theta_1,\theta_2+\pi/2)}$$

$$S=|-E(a,b)+E(a',b)+E(a,b')+E(a',b')|\leq 2$$

量子态	$\frac{1}{\sqrt{2}}(\lvert HV\rangle+\lvert VH\rangle)$	$\frac{1}{\sqrt{2}}(\lvert HV\rangle-\lvert VH\rangle)$	$\frac{1}{\sqrt{2}}(\lvert HH\rangle+\lvert VV\rangle)$	$\frac{1}{\sqrt{2}}(\lvert HH\rangle-\lvert VV\rangle)$
$E(\theta_1,\theta_2)$	$-\cos(2(\theta_1+\theta_2))$	$-\cos(2(\theta_1-\theta_2))$	$\cos(2(\theta_1-\theta_2))$	$\cos(2(\theta_1+\theta_2))$
θ_1	0	0	0	0
θ_1'	$\pi/4$	$\pi/4$	$\pi/4$	$\pi/4$
θ_2	$\pi/8$	$-\pi/8$	$-\pi/8$	$\pi/8$
θ_2'	$3\pi/8$	$-3\pi/8$	$-3\pi/8$	$3\pi/8$
Smax	2.68 ± 0.02	2.68 ± 0.02	2.63 ± 0.02	2.29 ± 0.03

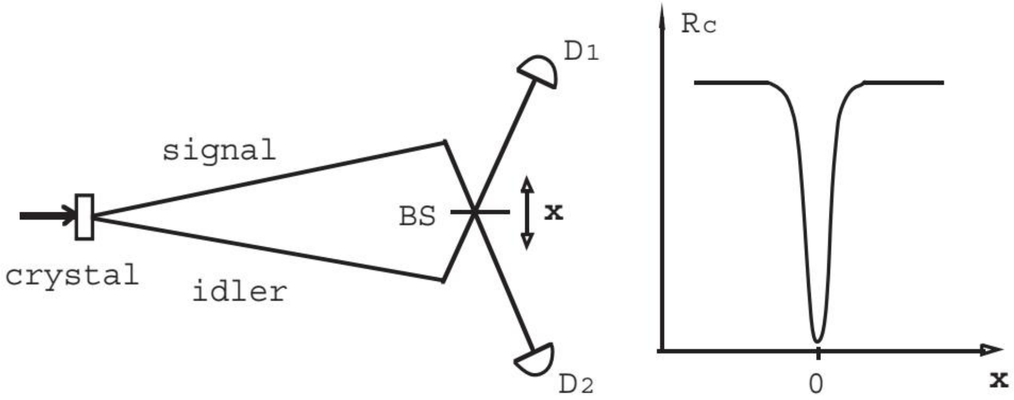


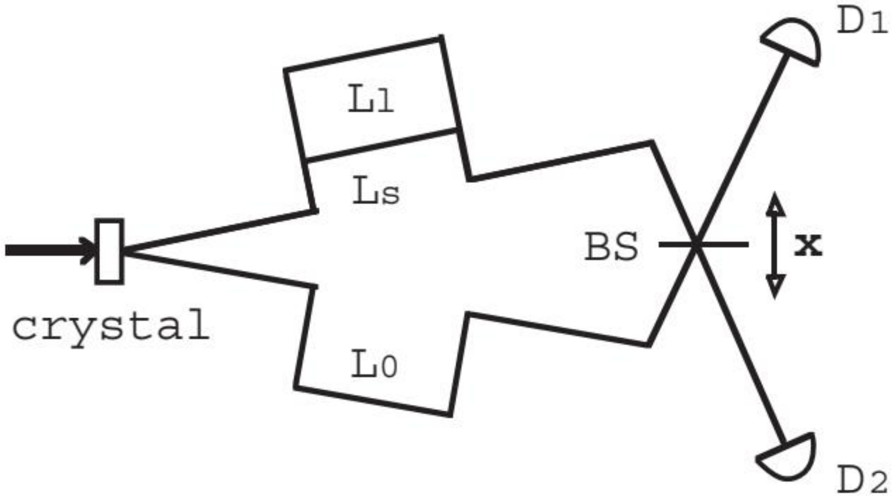


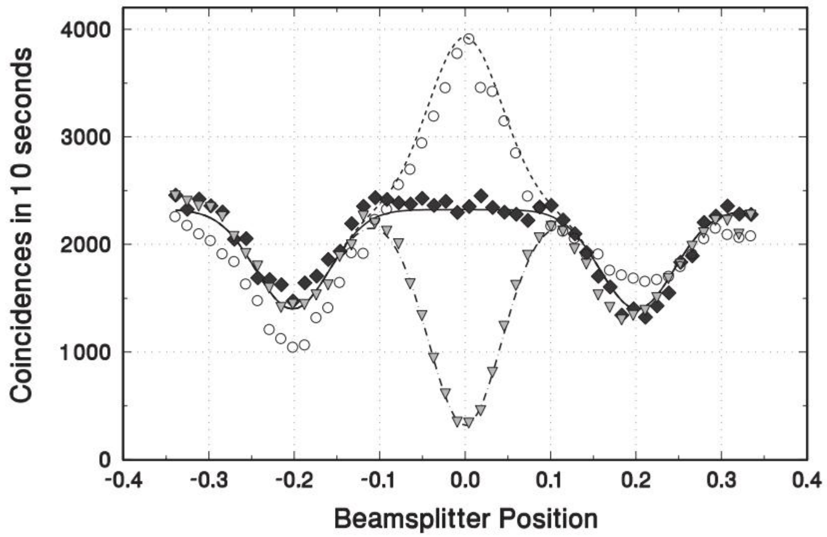
双光子量子干涉实验

Dirac stated that '. . .photon. . . only interferes with itself. Interference between two different photons never occurs'.

Is two-photon interference the interference of two-photons? 狄拉克说错了吗?

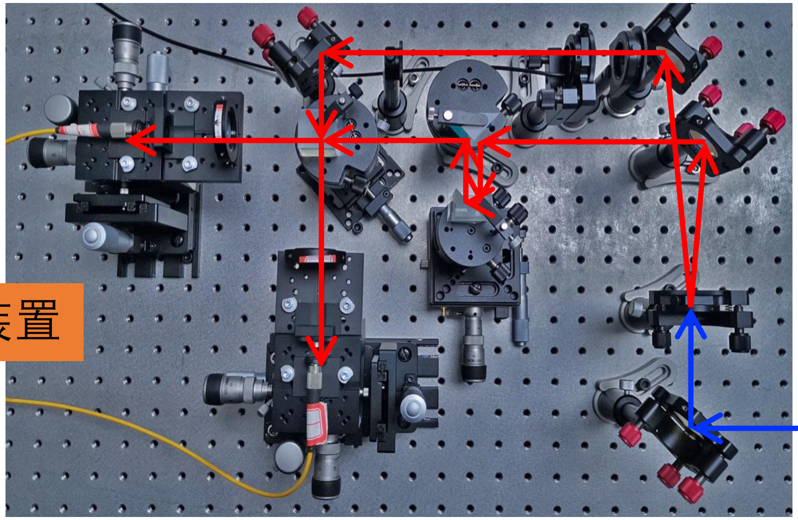




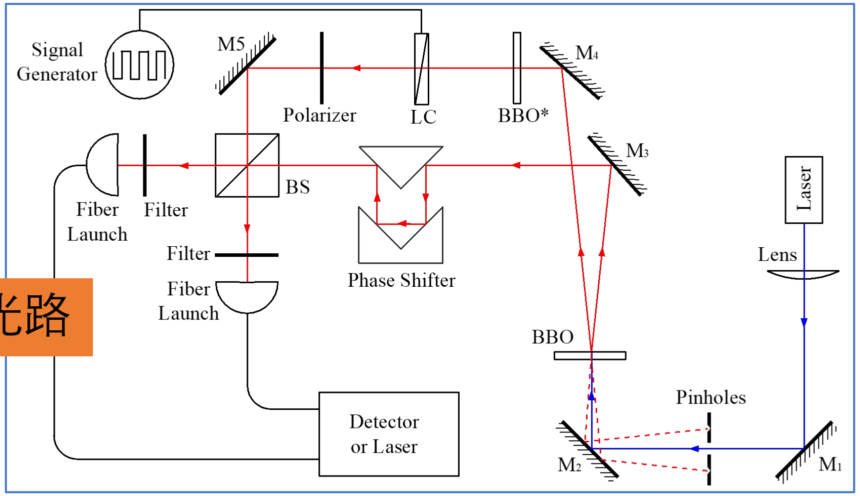


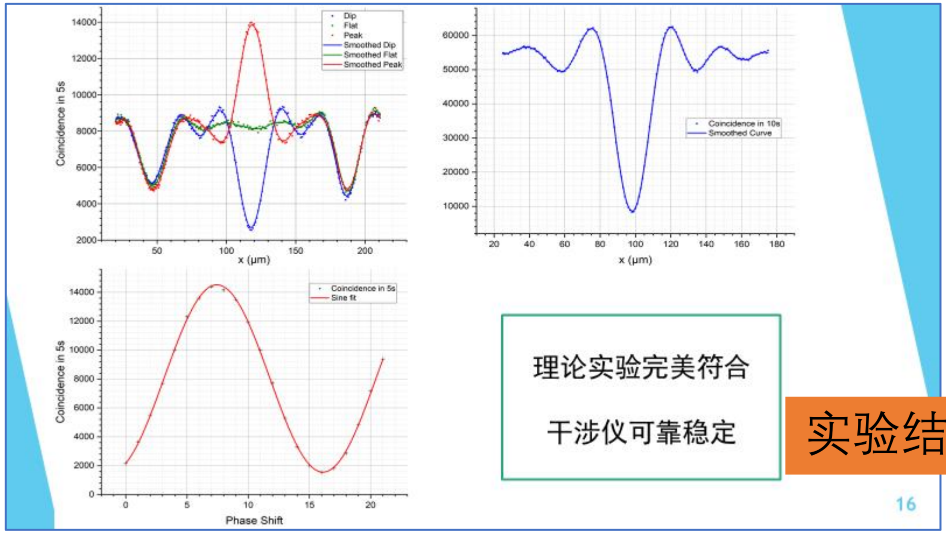
2021年创新赛自选题目一等奖

实验装置



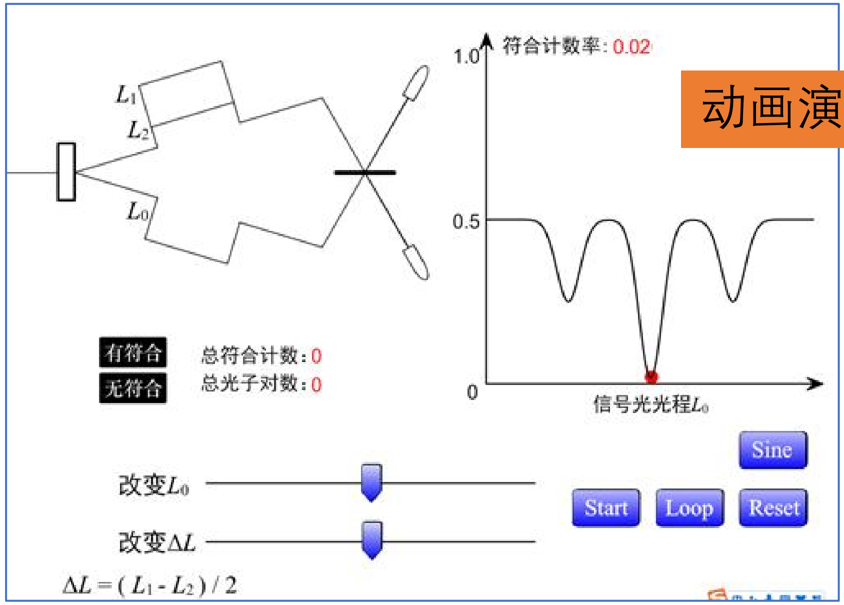
等效光路





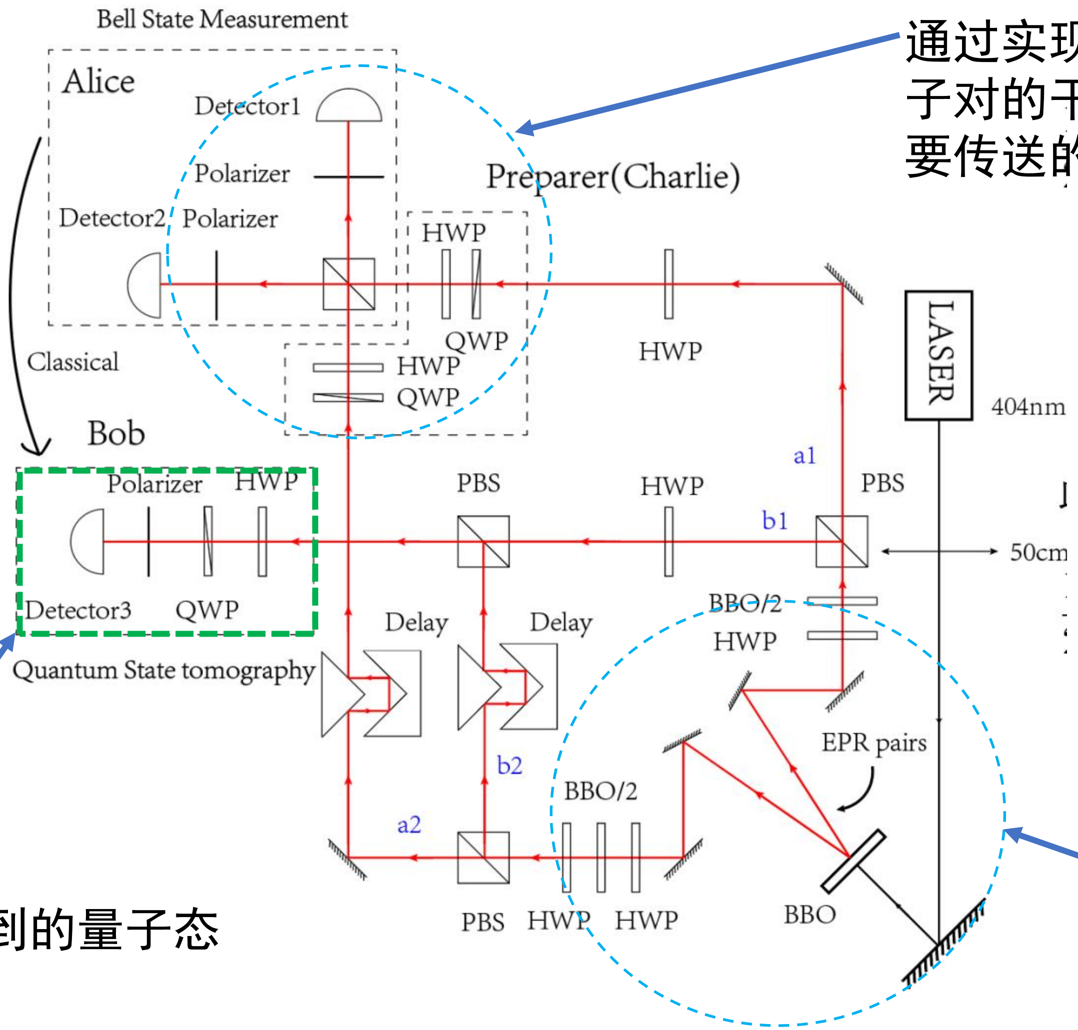
实验结果

动画演示



（4）双光子四比特量子隐形传态实验（进行中）

在 Type-II型SPDC纠缠双光子源的基础上，利用自由空间线性光学元件，通过光子多自由度量子特性，实现双光子四比特的量子隐形传态实验。



通过实现纠缠的光子对的干涉来制备要传送的量子态

检测传送到的量子态

产生纠缠的光子对

总结：

- 站在科研的高端，审视基础物理实验教学；
- 面向现代科技，梳理教学内容，优化教学体系；
- 发展典型实验案例，引导学生学习用实验方法研究物理问题；
- 以拔尖学生培养的实验教学为先导，带动基础物理实验教学的全面提高。