中国工程物理研究院
CHINA ACADEMY OF ENGINEERING PHYSICS

自旋相关标准模型之外的新相互作用探测研究

闫海洋

Spin

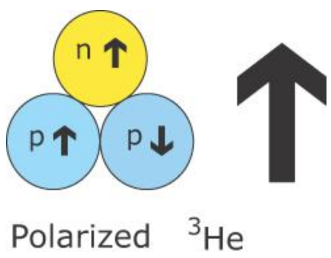
中国工程物理研究院核物理与化学研究所

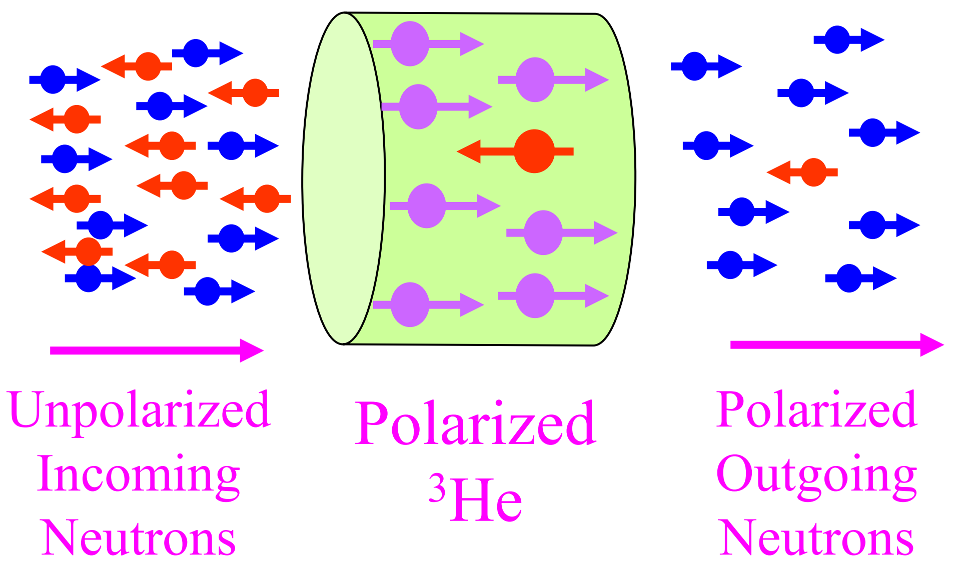
报告提纲

- 项目团队简介
- 研究背景
- 若干研究进展

团队及项目简介

极化3He中子自旋过滤器：



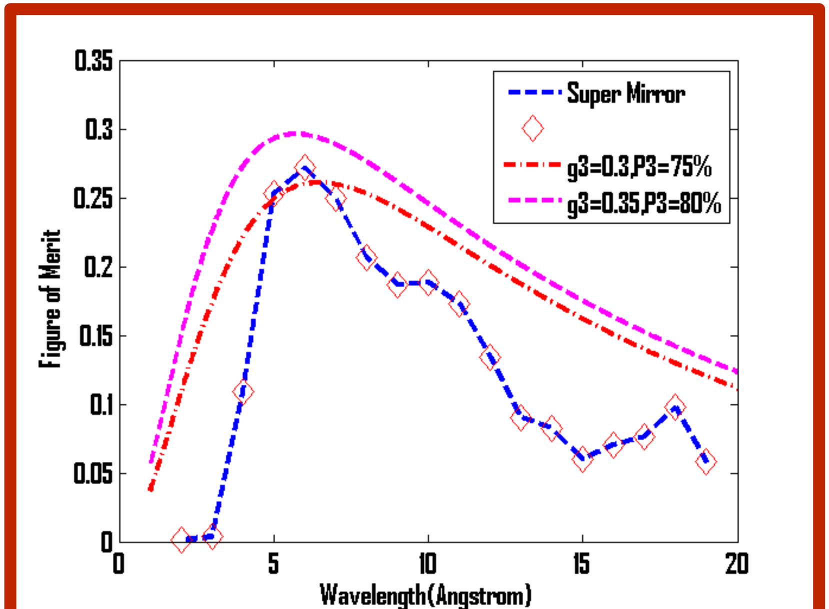


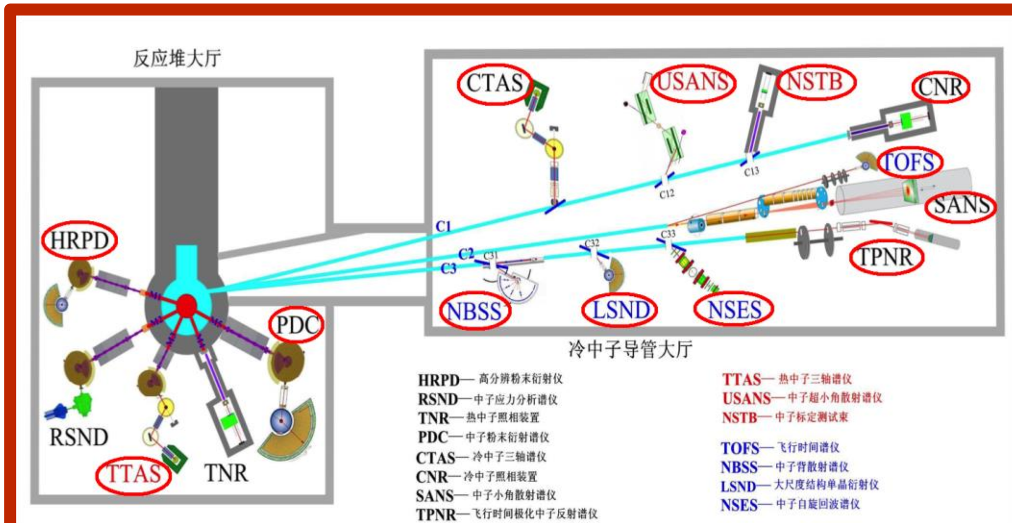
- 强烈的与自旋相关的中子吸收截面

团队及项目简介

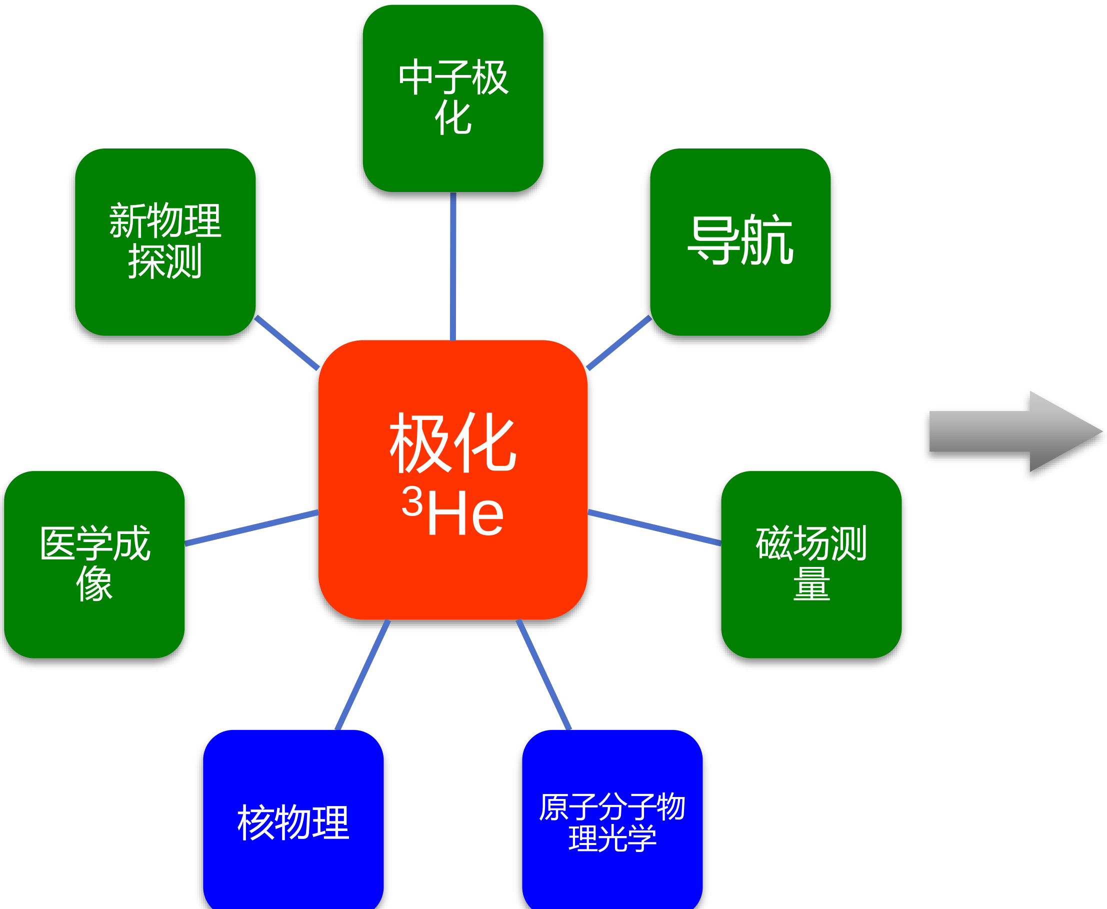
中物院二所绵阳堆的需求：

- 宽的中子工作谱
- 大的接收角
- 均匀的极化分析能力





极化^{3}He—多领域交叉的研究方向：



特点：

- 远远超过热平衡态的**高极化率**
- **长弛豫时间**
- **长相干时间**
- ~室温
- 低磁场~10G

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可用于做非常精确的核磁共振测量！

标准模型及问题


Standard Model
Quarks
Bosons
Leptons
u
up
d
down
c
charm
s
strange
t
top
b
bottom
γ
photon
g
gluon
W
W boson
Z
Z boson
H
Higgs boson
ν_e
electron neutrino
e
electron
ν_μ
muon neutrino
μ
muon
ν_τ
tau neutrino
τ
tau
Unknowns
Dark Matter
Extra Dimensions
Supersymmetry
Dark Energy
Unknown
Neutrino Mysteries
Inflation
W' & Z' Bosons
CP Violation
Dynamical EW Symmetry Breaking
Grand Unified Theories
Composite-ness
Cosmic Rays
Particle Data Group

标准模型的拉氏量：

$$\mathcal{L}_{SM} = -\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g^2_s f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$
$$M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c^2_w}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) -$$
$$igs_w(\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu -$$
$$W^-_\nu \partial_\nu W^+_\mu)) - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c^2_w (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu -$$
$$Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s^2_w (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w (A_\mu Z^0_\nu (W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \frac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 -$$
$$\beta_h\left(\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \frac{2M^4}{g^2}\alpha_h -$$
$$g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) -$$
$$\frac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) -$$
$$gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c^2_w}Z^0_\mu Z^0_\mu H -$$
$$\frac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) +$$
$$\frac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) +$$
$$M\left(\frac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\frac{s^2_w}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- -$$
$$W^-_\mu\phi^+) - ig\frac{1-2c^2_w}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) -$$
$$\frac{1}{4}g^2 W^+_\mu W^-_\mu\left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \frac{1}{8}g^2\frac{1}{c^2_w}Z^0_\mu Z^0_\mu\left(H^2 + (\phi^0)^2 + 2(2s^2_w - 1)^2\phi^+\phi^-\right) -$$
$$\frac{1}{2}g^2\frac{s^2_w}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s^2_w}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c^2_w - 1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^2 s^2_w A_\mu A_\mu\phi^+\phi^- + \frac{1}{2}ig_s\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial +$$
$$m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) +$$
$$\frac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s^2_w - 1 - \gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\frac{4}{3}s^2_w - 1 - \gamma^5)d^\lambda_j) +$$
$$(\bar{u}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s^2_w + \gamma^5)u^\lambda_j)\} + \frac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) +$$
$$\frac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) +$$
$$\frac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa\right) +$$
$$\frac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa\right) - \frac{g}{2}\frac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) -$$
$$\frac{g}{2}\frac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \frac{ig}{2}\frac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \frac{ig}{2}\frac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda) - \frac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa -$$
$$\frac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa + \frac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j\right) +$$
$$\frac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j\right) - \frac{g}{2}\frac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) -$$
$$\frac{g}{2}\frac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu +$$
$$\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \frac{M^2}{c^2_w})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- -$$
$$\partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 -$$
$$\partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ -$$
$$\partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ -$$
$$\partial_\mu\bar{X}^- X^-) - \frac{1}{2}gM\left(\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c^2_w}\bar{X}^0 X^0 H\right) + \frac{1-2c^2_w}{2c_w}igM\left(\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-\right) +$$
$$\frac{1}{2c_w}igM\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + igMs_w\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) +$$
$$\frac{1}{2}igM\left(\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0\right).$$

1
$$-\frac{1}{2}\partial_\nu g^a_\mu\partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g^2_s f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$
$$\frac{1}{2}ig^2_s(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu\partial_\nu W^-_\mu -$$

2
$$M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c^2_w}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu\partial_\mu A_\nu - \frac{1}{2}\partial_\mu H\partial_\mu H -$$
$$\frac{1}{2}m^2_h H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c^2_w}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} +$$
$$\frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu -$$
$$W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu -$$
$$W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$
$$\frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c^2_w(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$
$$g^2 s^2_w(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] -$$
$$\frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] -$$
$$gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c^2_w}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$
$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ -$$
$$\phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s^2_w}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) +$$
$$igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c^2_w}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$
$$igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] -$$
$$\frac{1}{4}g^2\frac{1}{c^2_w}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s^2_w - 1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s^2_w}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s^2_w}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c^2_w - 1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^1 s^2_w A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j -$$

3
$$\bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] +$$
$$\frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s^2_w - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s^2_w -$$
$$1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s^2_w - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) +$$
$$(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1 +$$
$$\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt{2}}\frac{m^\lambda_e}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] -$$

4
$$\frac{g}{2}\frac{m^\lambda_e}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) +$$
$$m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 -$$
$$\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) -$$
$$\frac{ig}{2}\frac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 -$$

5
$$\frac{M^2}{c^2_w})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- -$$
$$\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y -$$
$$\partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ -$$
$$\partial_\mu\bar{X}^- X^-) - \frac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c^2_w}\bar{X}^0 X^0 H] +$$
$$\frac{1-2c^2_w}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] +$$
$$igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]$$

强CP问题：强相互作用中为何CP守恒？

$$\mathcal{L}_{SM} = \cdots + \theta_{QCD} \frac{g_s^2}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

$\longrightarrow$ Chern-Simons项

中子的电偶极矩：

$$d_n \sim \theta_{QCD} \frac{m_u m_d}{m_u + m_d} \frac{1}{\Lambda_{QCD}} \frac{e}{m_n} \sim 3 \times 10^{-16} \theta_{QCD}\ e\,\text{cm}$$

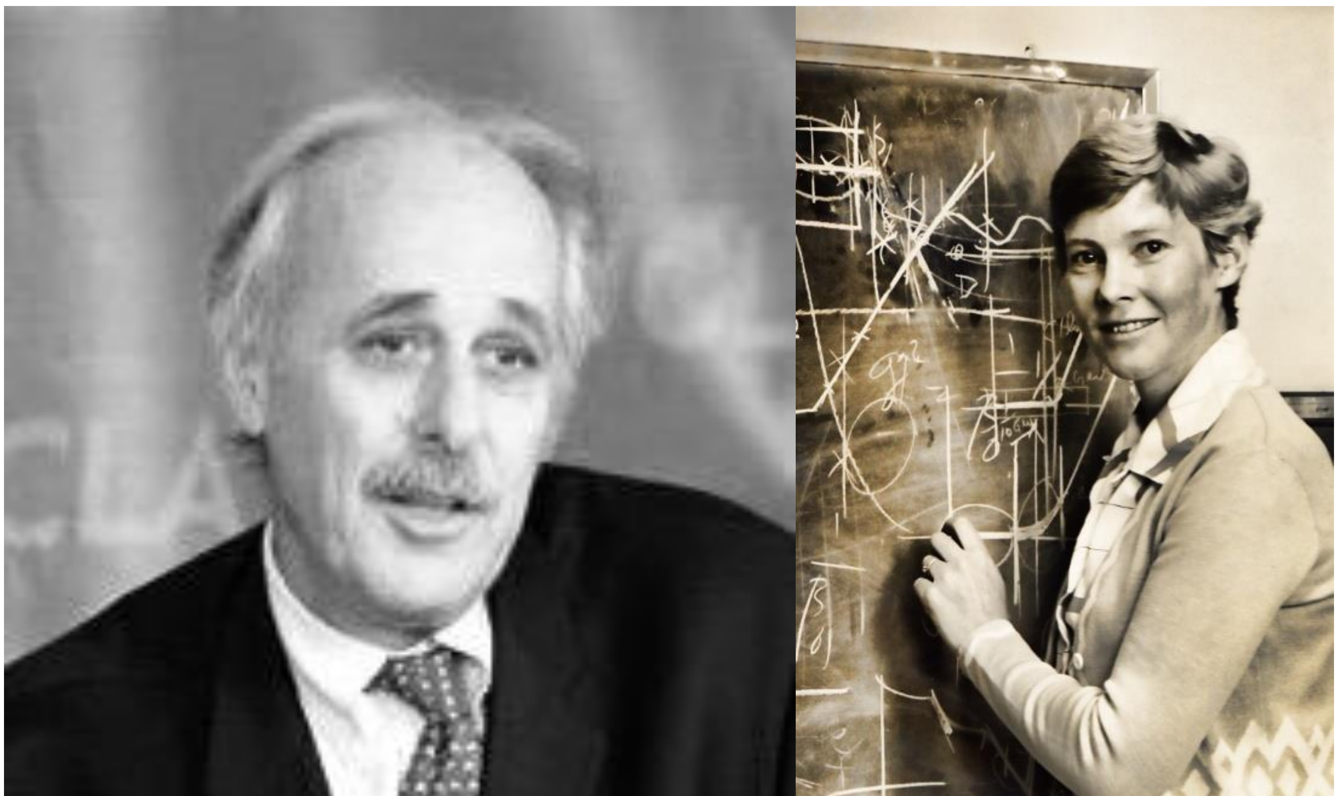
Θ非自然的小：

$$\theta_{QCD} \ll 10^{-10}$$

PQ机制：由Peccei和Quinn于1977年提出

引入一个新的全局对称性并令其自发破缺：

$$\mathfrak{L} = -\frac{1}{4} F_{\mu\nu}{}^{a} F^{\mu\nu a} + i\,\bar{\psi} D_{\mu}\gamma^{\mu}\psi + \bar{\psi}\left[G\varphi\,\tfrac{1}{2}(1+\gamma_5) + G^{*}\varphi^{*}\,\tfrac{1}{2}(1-\gamma_5)\right]\psi - |\partial_{\mu}\varphi|^2 - \mu^2|\varphi|^2 - h|\varphi|^4; \quad \mu^2 < 0.$$



R.Peccei与H.Quinn

W与W同时注意到Axion的产生：

), Number 4 PHYSICAL REVIEW LETTERS 23 January 1978

A New Light Boson?

Steven Weinberg
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 6 December 1977)

It is pointed out that a global U(1) symmetry, that has been introduced in order to preserve the parity and time-reversal invariance of strong interactions despite the effects of instantons, would lead to a neutral pseudoscalar boson, the "axion," with mass roughly of order 100 keV to 1 MeV. Experimental implications are discussed.

umber 5 PHYSICAL REVIEW LETTERS 30 January 1978

Problem of Strong *P* and *T* Invariance in the Presence of Instantons

F. Wilczek[a]
:olumbia University, New York, New York 10027, and The Institute for Advanced Studies, Princeton, New Jersey 08540[b]
(Received 29 November 1977)

The requirement that *P* and *T* be approximately conserved in the color gauge theory of strong interactions without arbitrary adjustment of parameters is analyzed. Several possibilities are identified, including one which would give a remarkable new kind of very light, long-lived pseudoscalar boson.

S.Weinberg与F.Wilczek

Axion：起源于一种洗衣粉

Frank Wilczek：

...我们认识到这个对称性意味着存在一种性质非常不一样的粒子——轴子（axion）（我用了一种洗衣粉的名字来命名这个粒子，因为它用轴矢流“清除”了一个问题）

“关于轴子物理已经有了大量的工作，也开过几次专门或部分讨论轴子的国际会议。经过多年大量的检验，它的核心思想发生了演化并且成熟了。另一方面，其他解决强P、T问题的方案的说服力都不能与之相比。

现在基础物理和宇宙学的一个重要目标是，要么证实轴子的存在，要么否定它。最近，世界上关于轴子的研究活动激增，表明这已经是一个被广泛接受的看法。”

轴子：

PHYSICAL REVIEW D VOLUME 30, NUMBER 1 1 JULY 1984

New macroscopic forces?

J. E. Moody* and Frank Wilczek
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106
(Received 17 January 1984)

The forces mediated by spin-0 bosons are described, along with the existing experimental limits. The mass and couplings of the invisible axion are derived, followed by suggestions for experiments to detect axions via the macroscopic forces they mediate. In particular, novel tests of the *T*-violating axion monopole-dipole forces are proposed.

$$\mathcal{L}_\phi = \bar{\psi}(g_s + i g_p \gamma_5)\psi\phi \longrightarrow V_{SP}(r) = \frac{\hbar^2 g_S g_P}{8\pi m_e}\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right)\exp(-r/\lambda)\vec{\sigma}\cdot\hat{r}$$

1.量子色动力学中的**强CP问题**最优雅的解决方案；

2.非常难探测，和普通粒子只有极弱的耦合-- 暗物质可能的候选者；

3.类轴子粒子可传播宏观相互作用，可通过探测源物质所产生的玻色场来探测；

4.传播自旋相关的新相互作用，需要利用极化自旋。

Axion Like Particles：类轴子粒子

自旋1玻色子耦合拉氏量:

$$\mathcal{L}_X = \bar{\psi}(g_V\gamma^\mu + g_A\gamma^\mu\gamma_5)\psi X_\mu$$

$$V_{VA}(r) = \frac{\hbar g_V g_A}{2\pi}\frac{\exp(-r/\lambda)}{r}\vec{\sigma}\cdot\vec{v}$$

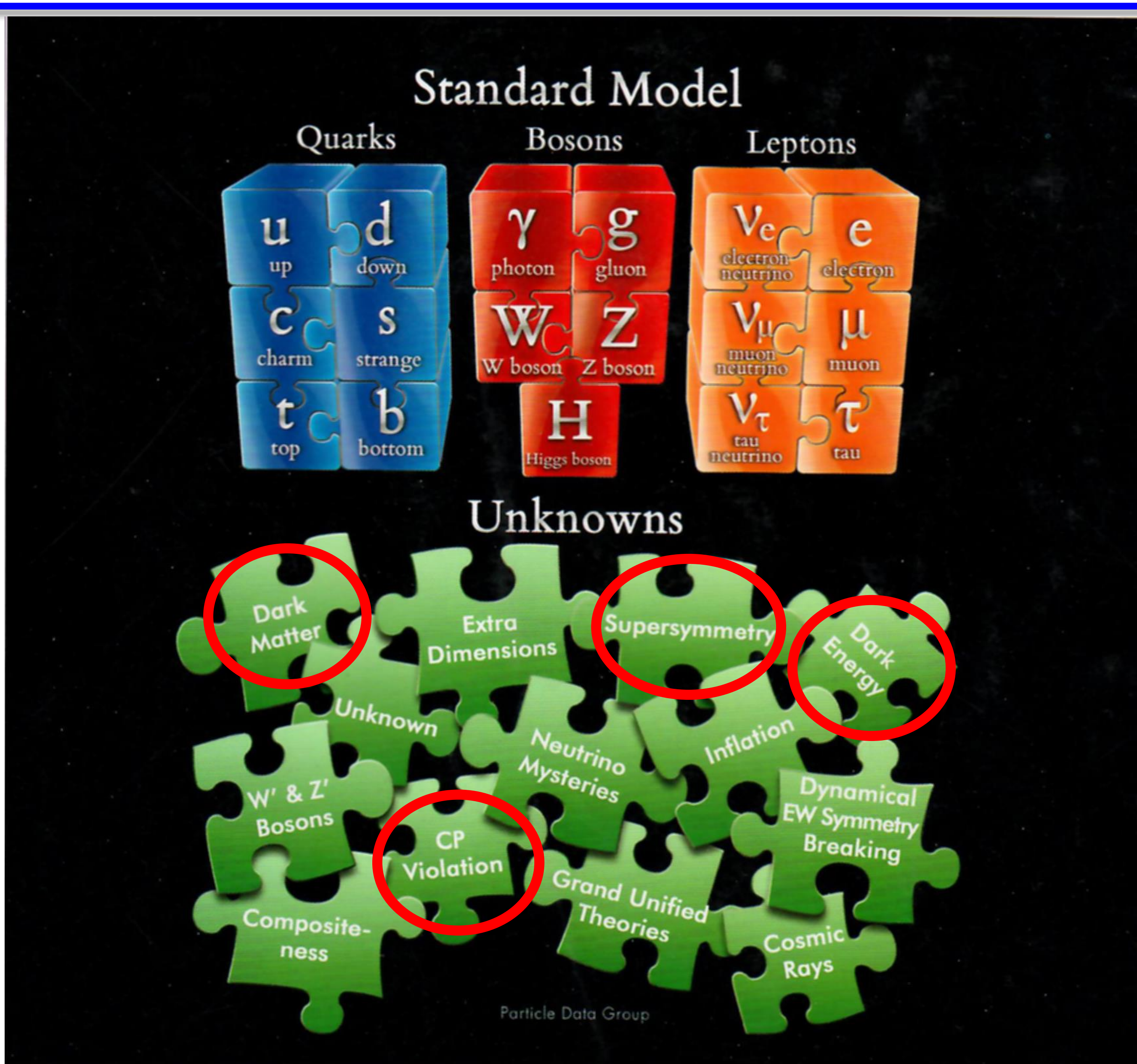
$$V_{AA}(r) = \frac{\hbar^2 g_A^2}{16\pi mc}\left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)\exp(-r/\lambda)\vec{\sigma}\cdot(\vec{v}\times\hat{r})$$

1.**Dobrescu等人的推广工作—新相互作用传播粒子可以是自旋1的；**

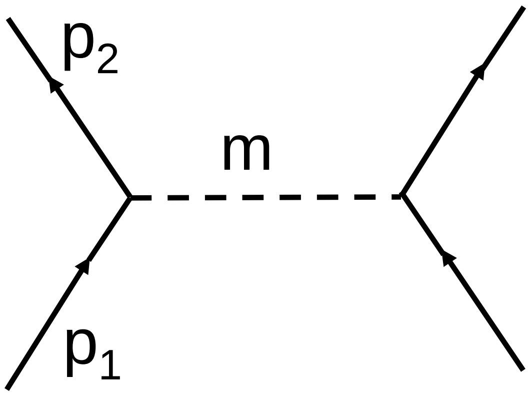
2.Fayet注意到超对称理论自发破缺将产生轻质量弱耦合自旋1粒子。

B. Dobrescu and I. Mocioiu, J. High Energy Phys. 11, 005(2006).
P.Fayet， Phys. Lett., 95B(2), 285, (1980).

类轴子粒子：与最重要物理问题的解



适合精密测量的情形：



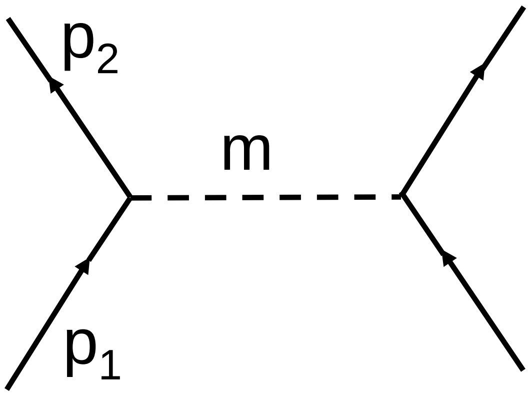
$$q = p_1 - p_2$$

$$f(q^2) \propto \frac{1}{q^2 - m^2}$$

- 当 m 很大时:

$$f(q^2) \propto \frac{1}{-m^2}$$

适合精密测量的情形：

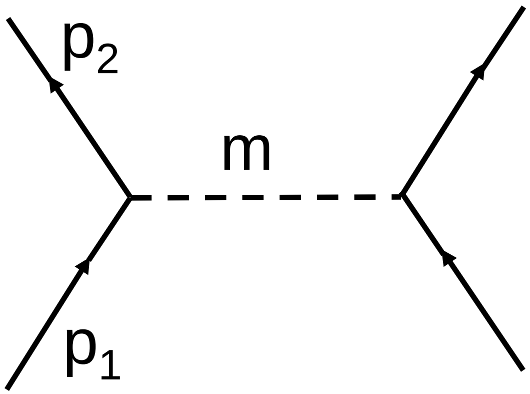


$$q = p_1 - p_2$$

$$f(q^2) \propto \frac{1}{q^2 - m^2}$$

- 当 m 很大时: $f(q^2) \propto \frac{1}{-m^2}$
- 当m 很小时: $f(q^2) \propto \frac{1}{q^2}$

适合精密测量的情形：



$$q = p_1 - p_2$$

$$f(q^2) \propto \frac{1}{q^2 - m^2}$$

- 当 m 很大时: $$f(q^2) \propto \frac{1}{-m^2}$$
- 当m 很小时: $$f(q^2) \propto \frac{1}{q^2}$$
- 极化相关的测量：与能量没有关系！

用极化自旋测量基本对称性：

Question of Parity Conservation in Weak Interactions*

T. D. Lee, *Columbia University, New York, New York*

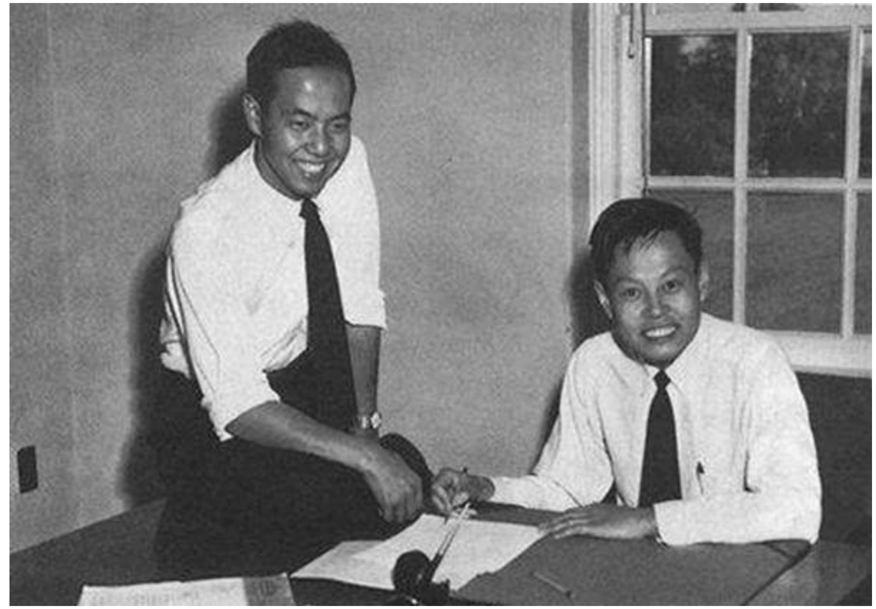
AND

C. N. Yang,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

The reason for the absence of interference terms CC' is actually quite obvious. Such terms can only occur as a pseudoscalar formed out of the experimentally measured quantities. For example, if three momenta $\mathbf{p}_1$, $\mathbf{p}_2$, $\mathbf{p}_3$ are measured, the term $CC'\mathbf{p}_1\cdot(\mathbf{p}_2\times\mathbf{p}_3)$ may occur. Or if a momentum $\mathbf{p}$ and a spin $\boldsymbol{\sigma}$ are measured, the term $CC'\mathbf{p}\cdot\boldsymbol{\sigma}$ may occur. In all the β-decay phenomena mentioned above, no such pseudoscalars can be formed out of the measured quantities.



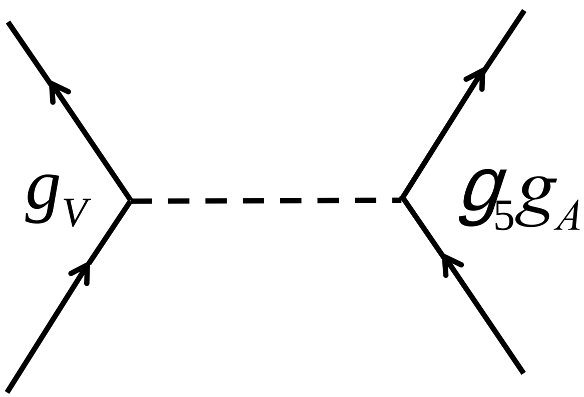
- In their historic paper, they pointed out that a pseudo scalar has to be formed to observe parity violation:

$$\mathbf{p}_1 \bullet (\mathbf{p}_2 \times \mathbf{p}_3) \quad \text{or} \quad \mathbf{p} \bullet \boldsymbol{\sigma}$$

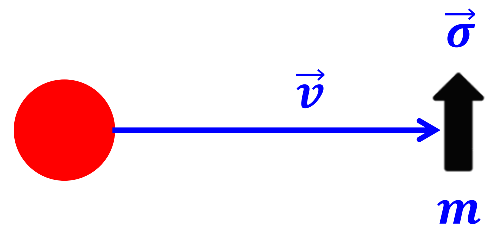
- For T violation:

$$\mathbf{r} \bullet \boldsymbol{\sigma}$$

新物理与新相互作用:VA耦合

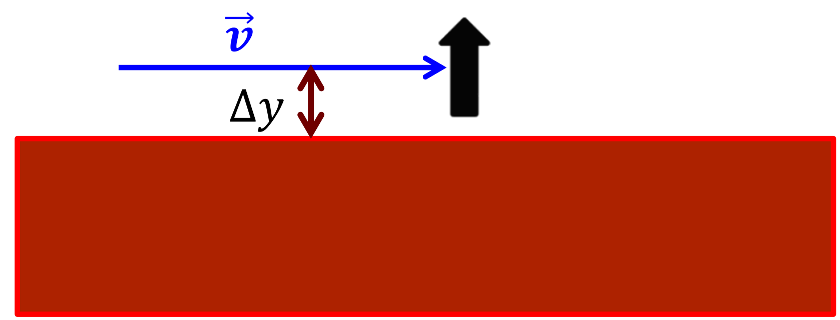


$$L_I = \bar{\psi}(g_V \gamma^\mu + g_A \gamma^\mu \gamma_5)\psi X_\mu$$



$$V(r) = \frac{\hbar}{2\pi} g_V g_A \vec{\sigma} \bullet \vec{v} \frac{1}{r} e^{-\frac{r}{\lambda}}$$

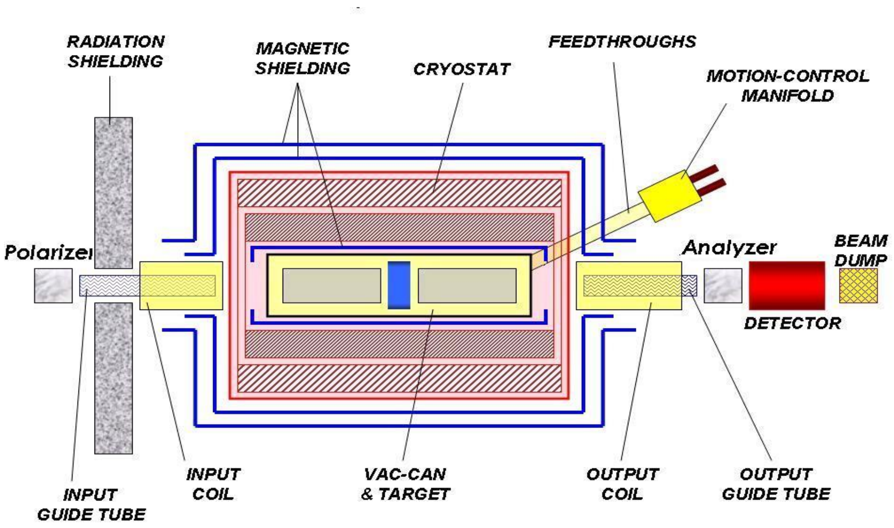
对于一个厚度为d的平板样品:



$$\vec{B}_{VA} = \frac{2}{\gamma_n} g_V g_A \rho_N \lambda^2 e^{-\frac{\Delta y}{\lambda}}[1 - e^{-\frac{d}{\lambda}}]\vec{v}$$

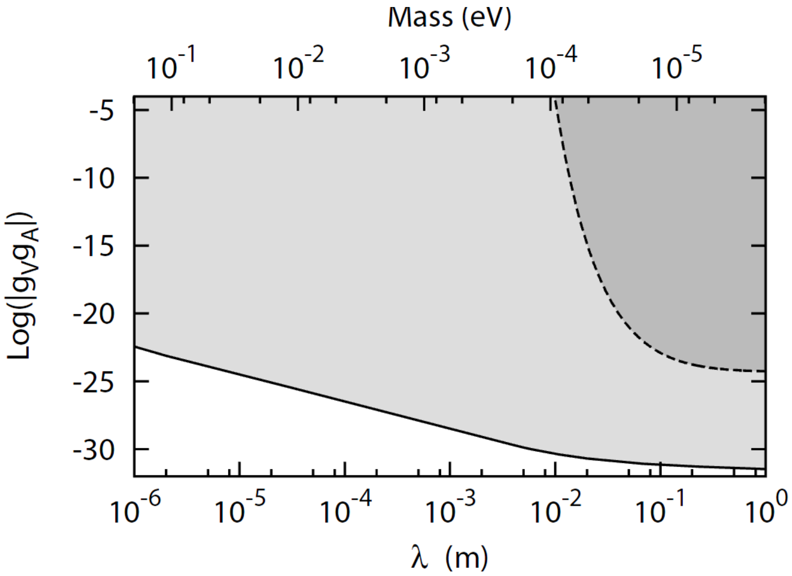
B. Dobrescu and I. Mocioiu, J. High Energy Phys. 11, 005(2006).

极化中子在液氦中自选旋转探测新物理



$$\frac{d\varphi}{dL} < 9.2\times 10^{-7} rad/m$$

实验探测灵敏度超过普林斯顿大学组已有结果7个数量级以上



H.Yan and W.M.Snow, Phys. Rev. Lett.110, 082003(2013).

极化^{3}He自旋弛豫时间探测新物理

$$\vec{B}_{VA}=\frac{2}{\gamma_n}g_V g_A\rho_N\lambda^2 e^{-\frac{\Delta y}{\lambda}}[1-e^{-\frac{d}{\lambda}}]\vec{v}$$

- 非极化源对自旋的作用；
- 探测粒子自旋需极化；
- 探测粒子与源之间有一个小的间距；
- 测粒子与源之间有一个大的相对速度。

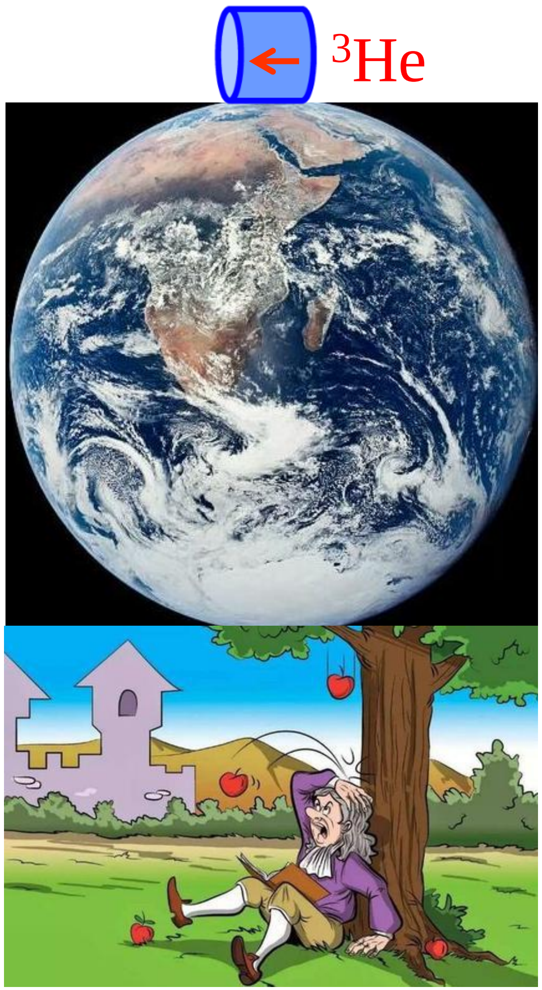
极化^{3}He自旋弛豫时间探测新物理

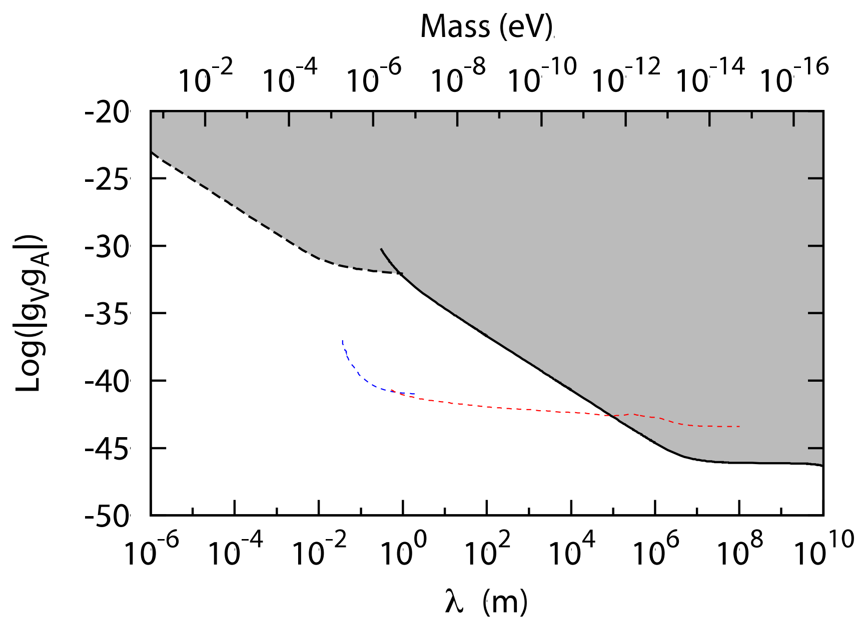
$$\vec{B}_{VA} = \frac{2}{\gamma_n} g_V g_A \rho_N \lambda^2 e^{-\frac{\Delta y}{\lambda}} [1 - e^{-\frac{d}{\lambda}}] \vec{v}$$

- 自旋旋转效应 ~ B，一阶效应；
- 弛豫时间效应 ~ <B^2>，二阶效应；
- 弛豫时间效应不需要移动实验仪器来实现相对速度；

  静止的3He气室，<v>=0 但是<v^2>≠0
- 如何克服二阶效应的缺点?

使用极化^{3}He自旋驰豫时间探测标准模型之外的新物理

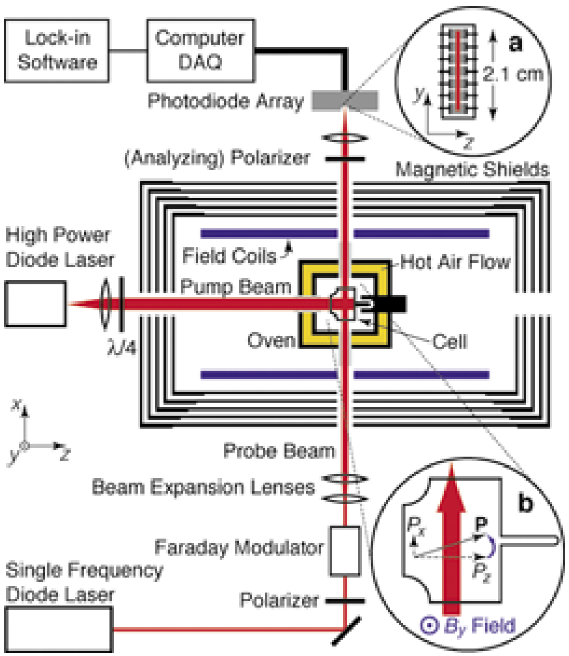


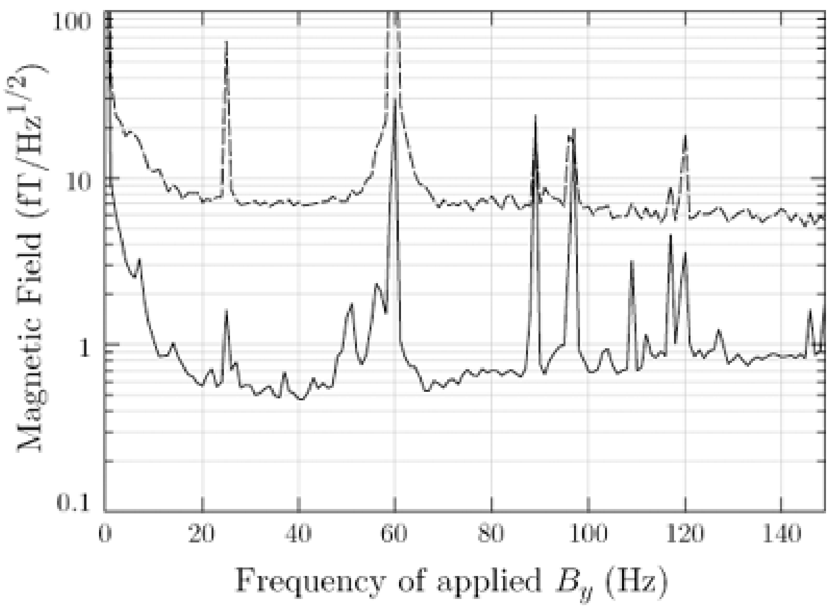


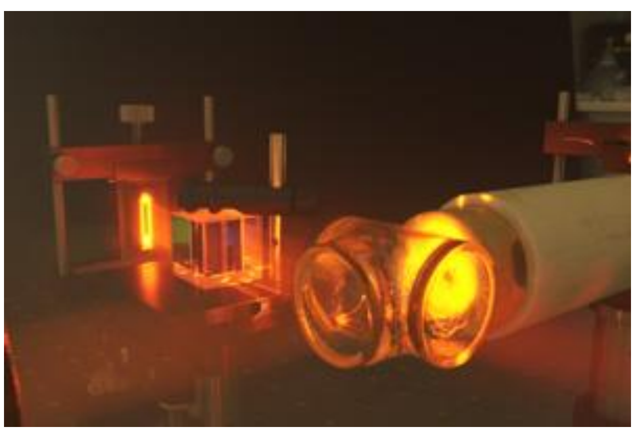
- 用地球作为质量源；
- 使用已知最长的自旋驰豫时间.

H.Yan*,G.A.Sun,S.M.Peng,Y.Zhang,C.Fu,H.Guo and B.Q.Liu, Physical Review Letters, 115, 182001 (2015)

SERF磁强计：基于极化碱金属自旋并具有高灵敏度

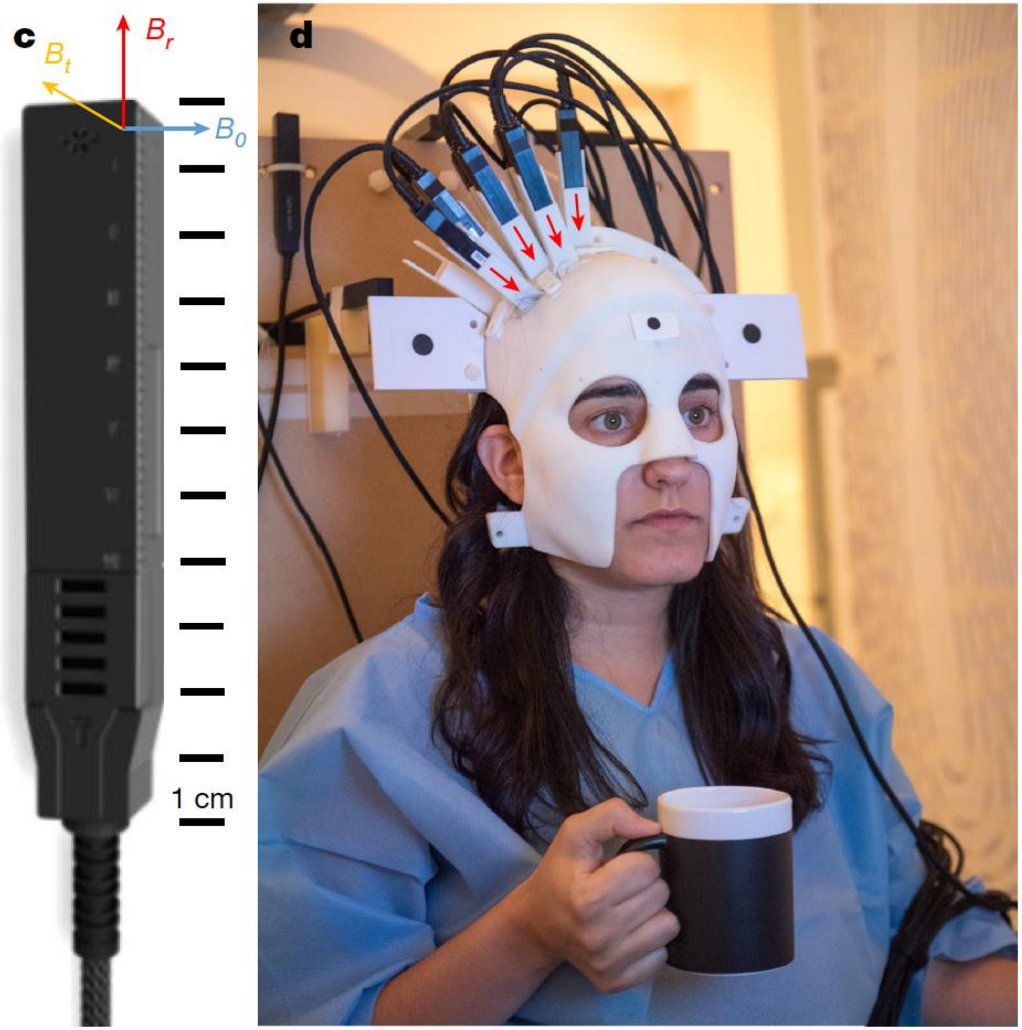






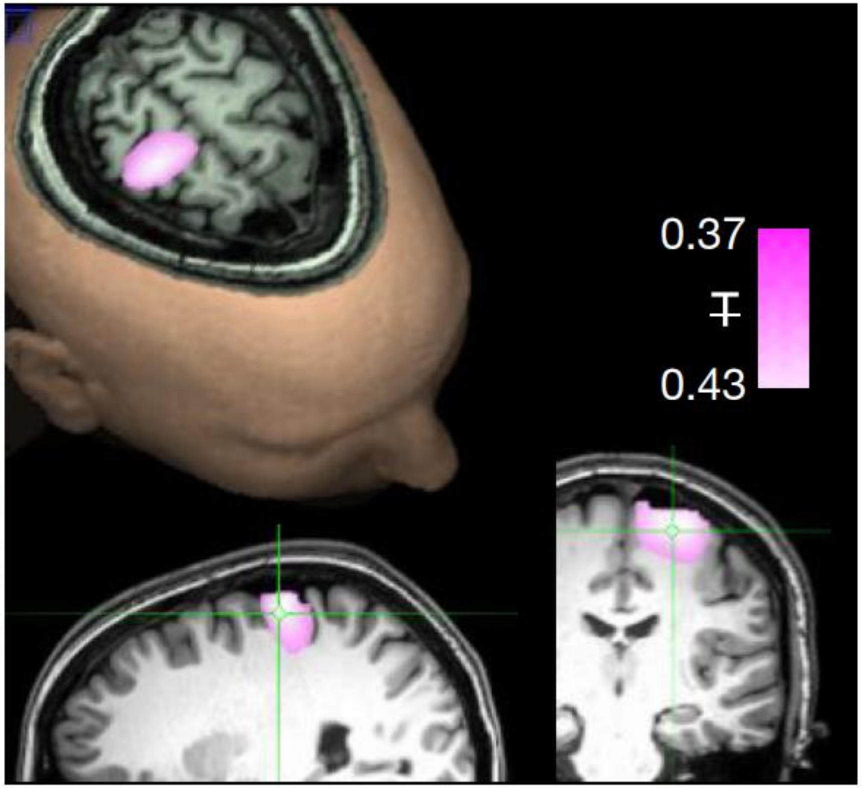
I. K. Kominis, T. W. Kornack, J. C. Allred & M. V. Romalis, "A subfemtotesla multichannel atomic magnetometer." *Nature* **422**, 596 (2003).

SERF磁强计：对于脑磁信号的测量



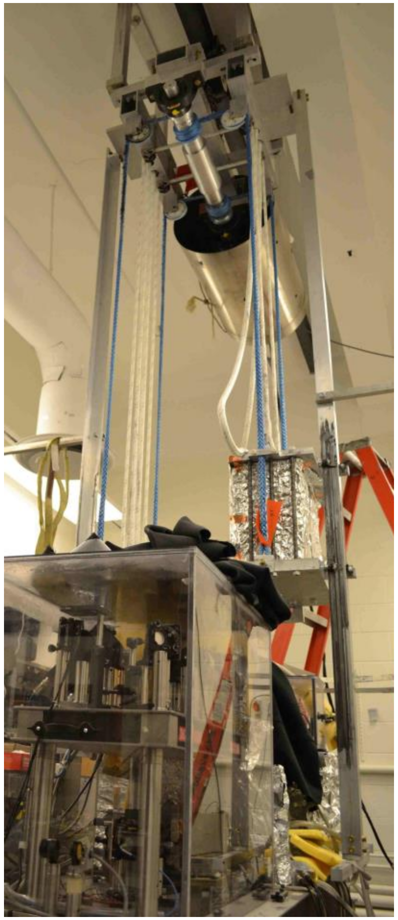
Nature **volume 555**, pages657–661 (2018)

SERF磁强计：对于脑磁信号的测量



Nature **volume 555**, pages657–661 (2018)

存在问题分析：信号调制频率



J. Lee, A.Almasi, and M. Romalis, PRL,120, 161801 (2018)

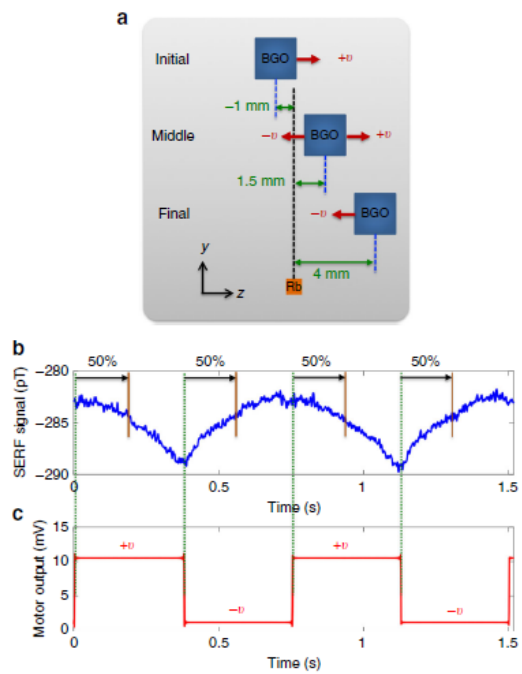


Fig. 3 Data collection. **a** A repeated bismuth germanate insulator (BGO) mass linear motion with respect to the rubidium vapor (not scaled). The BGO mass was extended with $v = 15.38$ mm s^{-1} for 0.325 s from the initial configuration to the final configuration and then retracted toward the initial configuration with $v = -15.38$ mm s^{-1} for 0.325 s, by a motor. **b** Time traces of spin-exchange relaxation-free (SERF) magnetometer signal showing two full cycles of the mass linear motion reversal. **c** The voltage output from the motor indicating the motion's direction which was high and low at extraction and retraction of the mass. The rising and falling edges served as the reference points for each half cycle

Y.J.Kim, P.H.Chu, I.Savukov & S. Newman, NC, 10:2245,(2019)

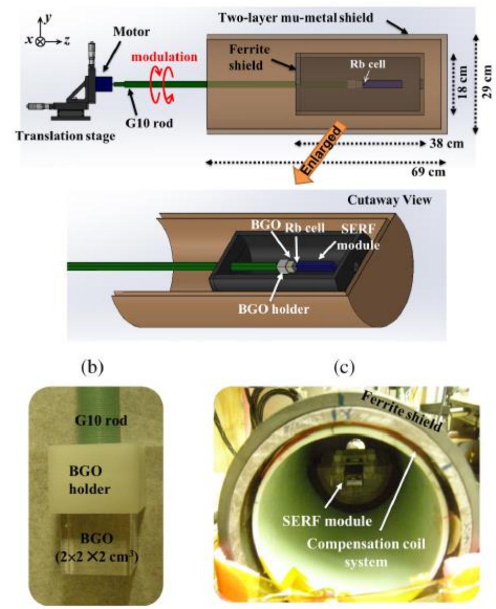
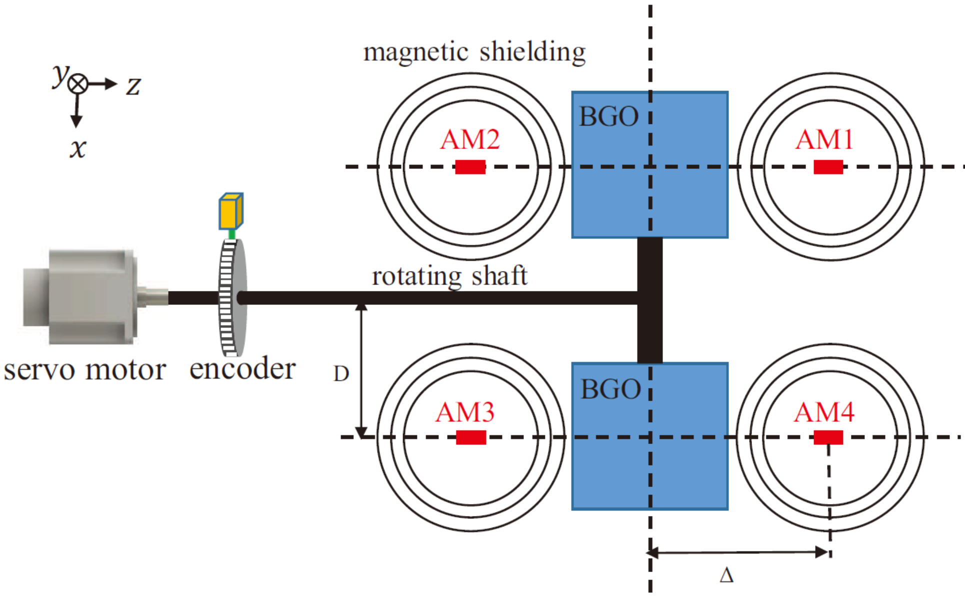
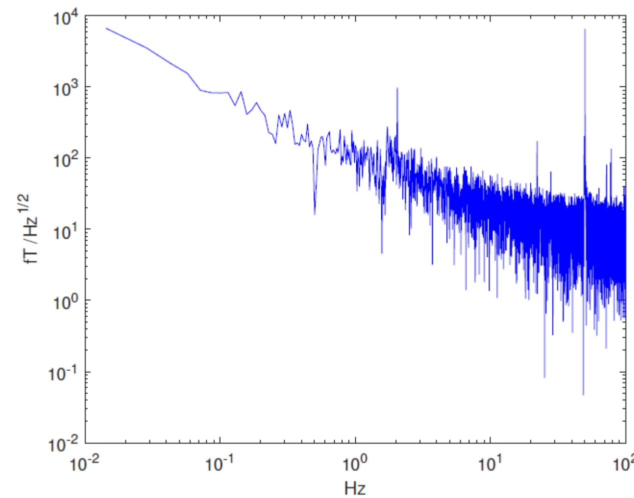


FIG. 1. (a) Side view of a schematic of the experimental setup to probe the exotic spin-dependent interaction V_{4+5}. An unpolarized BGO mass is placed next to a Rb vapor cell located inside the head of a SERF magnetometer module. The polarized Rb electron spins are oriented along the y axis. The mass is rotated clockwise and counterclockwise around the z axis to reduce systematic effects. (b) Photograph of the BGO mass connected to a G10 rod via a plastic holder to precisely control the position of the mass by using a three-axis translation stage. (c) Photograph of the SERF magnetometer module located inside a cylindrical ferrite shield (end cap not shown) that includes compensation coils to remove the residual field inside the shield.

Y.J.Kim, P.H.Chu, I.Savukov, PRL, 121,091802,(2018)

所提出的实验方案：





典型极化碱金属原子磁强计噪声功率谱密度

高频转动调制质量源+阵列原子磁强计：

1.调制频率20Hz，获得~40倍的噪声降低；
2.使用阵列磁强计，增加统计性并消除共模噪声

$$V_{SP}(r) = \frac{\hbar^2 g_S g_P}{8\pi m_e}\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right)\exp\left(-r/\lambda\right)\vec{\sigma}\cdot\hat{r}$$

$$\begin{aligned} B_{1z} &= B'_{SP_z} + B_{com} + B_{bg} \\ B_{2z} &= -B'_{SP_z} + B_{com} + B_{bg} \\ B_{3z} &= -B'_{SP_z} + B_{com} + B_{bg} \\ B_{4z} &= B'_{SP_z} + B_{com} + B_{bg} \end{aligned}$$

$$\begin{aligned} B'_{P_z} &= \frac{1}{4}(B_{1z} - B_{2z} + B_{3z} - B_{4z}) \\ &= B'_{P_z} + \sqrt{{B_{bg}}^2 + {B_{bg}}^2 + {B_{bg}}^2 + {B_{bg}}^2} \\ &= B'_{P_z} + \frac{1}{2}B_{bg} \end{aligned}$$

Phys. Rev. D **105**, 055020（2022）

数据处理方法:

$$\vec{B'}_{VA}(\vec{r}) = \frac{g_V g_A}{\pi\gamma_e}\int d^3\vec{r'}\frac{\exp(-|\vec{r}-\vec{r'}|/\lambda)}{|\vec{r}-\vec{r'}|}\vec{v}$$

$$\vec{B'}_{AA}(\vec{r}) = \frac{\hbar g_A^2}{8\pi m_e c\gamma_e}\int d^3\vec{r'}\left(\frac{1}{\lambda|\vec{r}-\vec{r'}|}+\frac{1}{|\vec{r}-\vec{r'}|^2}\right)\times \exp(-|\vec{r}-\vec{r'}|/\lambda)\left(\vec{v}\times\frac{\vec{r}-\vec{r'}}{|\vec{r}-\vec{r'}|}\right)$$

$$g_V g_A = g_A^2 = 1$$

$$B'(t) = c_0 + \sum_{n=1}^{\infty} c_n\cos(n\omega_0 t+\phi)$$

$$c_n = \frac{2}{NT}\int_0^{NT}\cos(n\omega_0 t+\phi)\,B'(t)dt$$

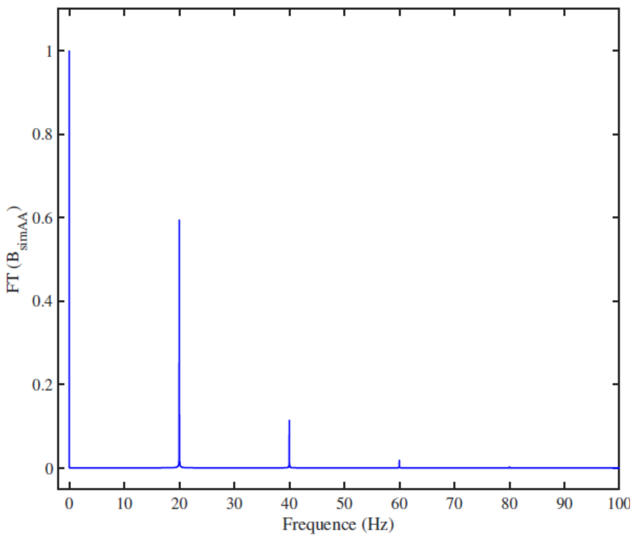
$$B_{\text{exp}}(t) = \alpha c_0 + \alpha\sum_{n=1}^{\infty} c_n\cos(n\omega_0 t+\phi) + n(t)$$

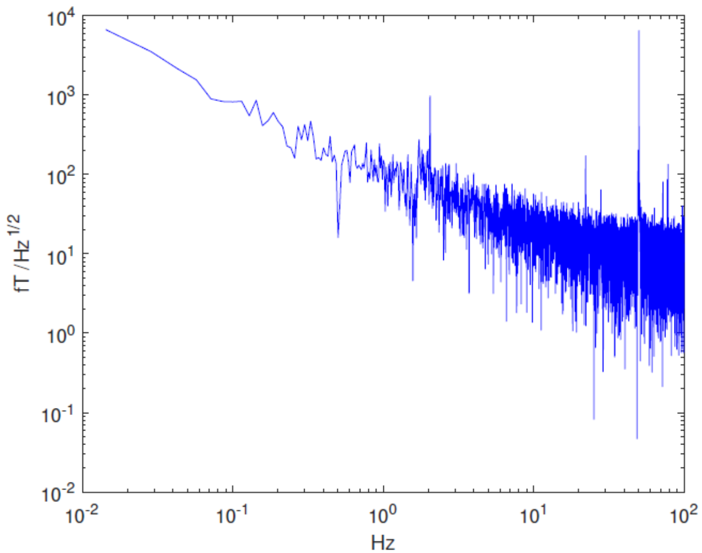
$\alpha = g_V g_A$ for the VA interaction

$\alpha = g_A^2$ for the AA interaction

$$\alpha|_n = \frac{2\int_0^{NT}\cos(n\omega_0 t+\phi)\,B_{exp}(t)dt}{c_n NT}$$

$$\delta\bar{\alpha}|_{noise} \sim \sqrt{S_N(nf_0)}\sqrt{\frac{2}{NT}}\frac{1}{\sqrt{\sum_{n=1}^{4} c_n^2}}$$



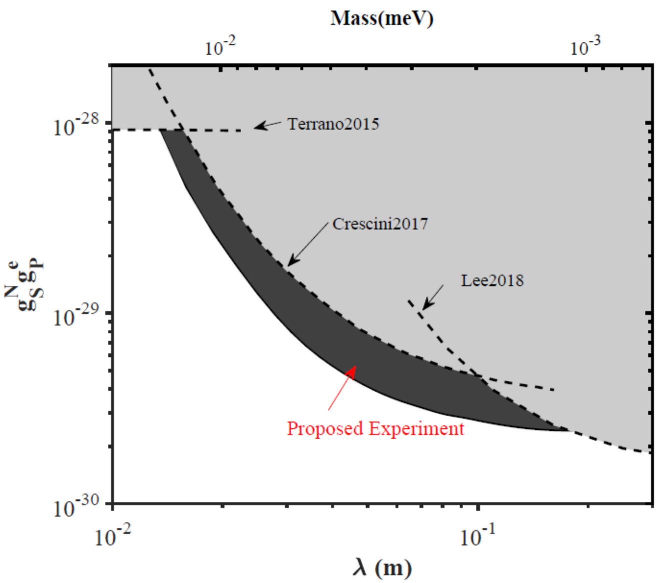


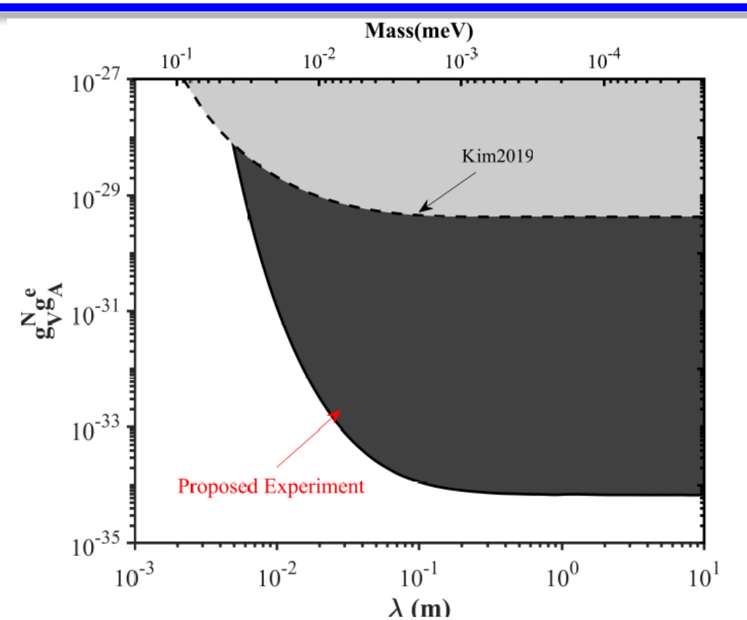
$$\bar{\alpha} = \frac{\sum_{n=1}^{4} c_n^2\alpha|_n}{\sum_{n=1}^{4} c_n^2}$$

30天~10aT的测量精度

Phys. Rev. D **105**, 055020(2022)

研究目标



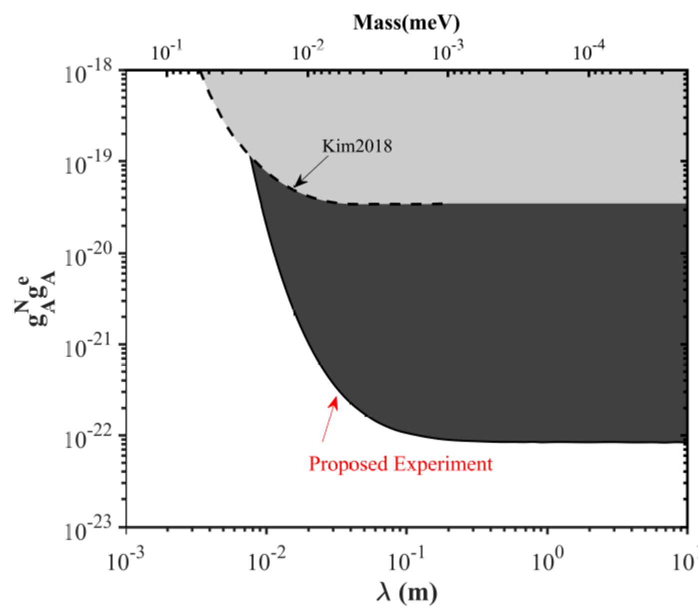


经蒙特卡洛模拟验证对V_{SP}、V_{VA}和V_{AA}由类轴子粒子所传播自旋相关新相互作用给出新的探测灵敏度（30天积分时间）：

1.V_{SP}比已有最高灵敏度提高~1.5倍；

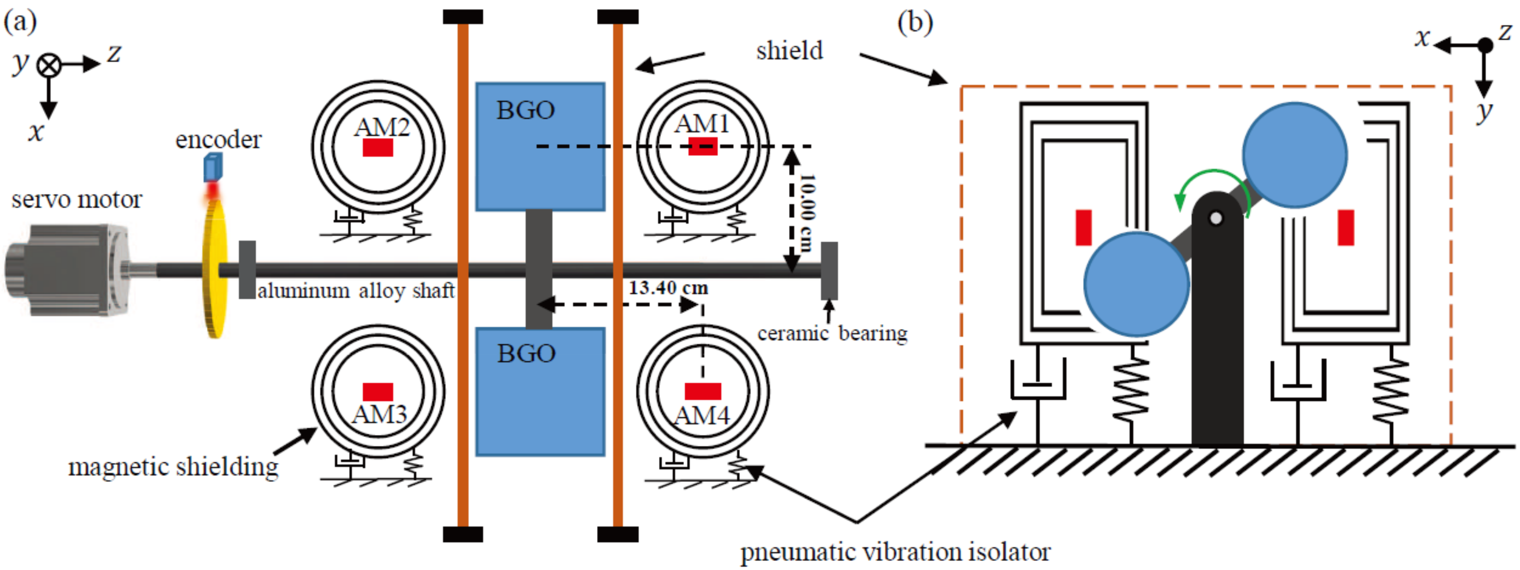
2.V_{VA}比已有最好结果提高~5个数量级；

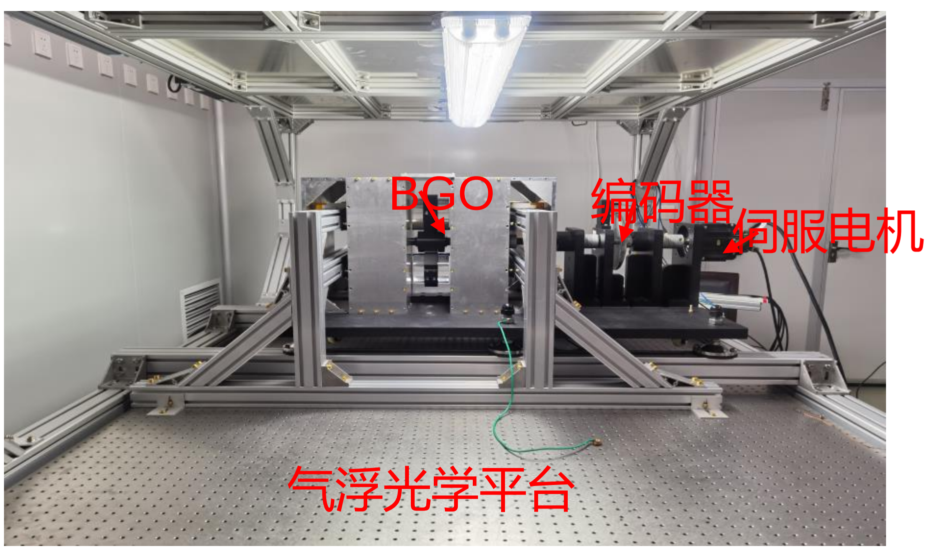
3.V_{AA}比已有最好结果提高~3个数量级。

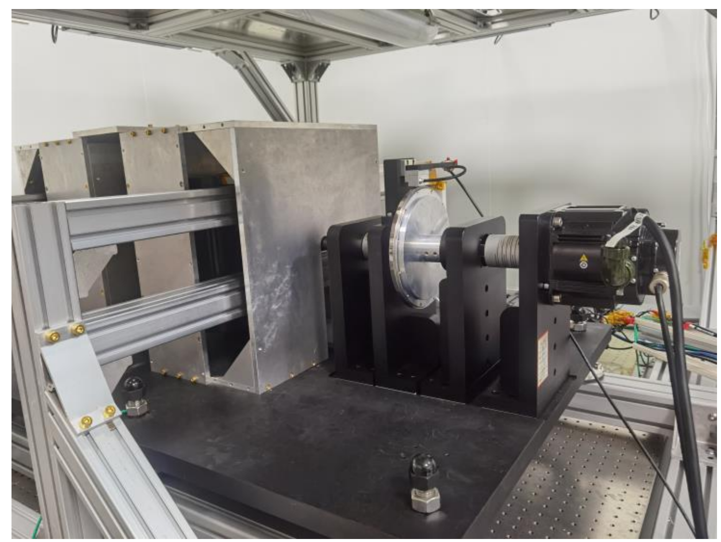


Phys. Rev. D **105**, 055020（2022）

实验实现：







Phys. Rev. Lett. **129** 051802 (2022)

数据案例:

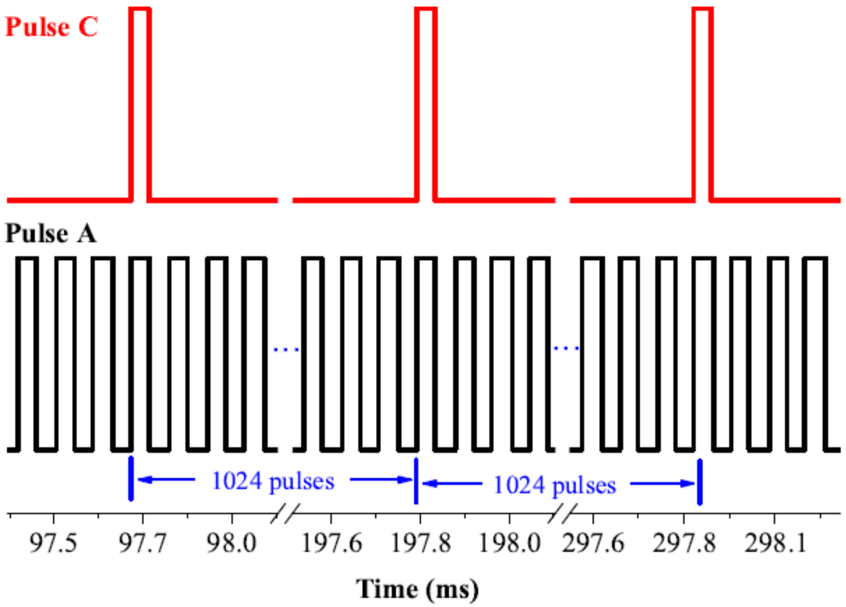
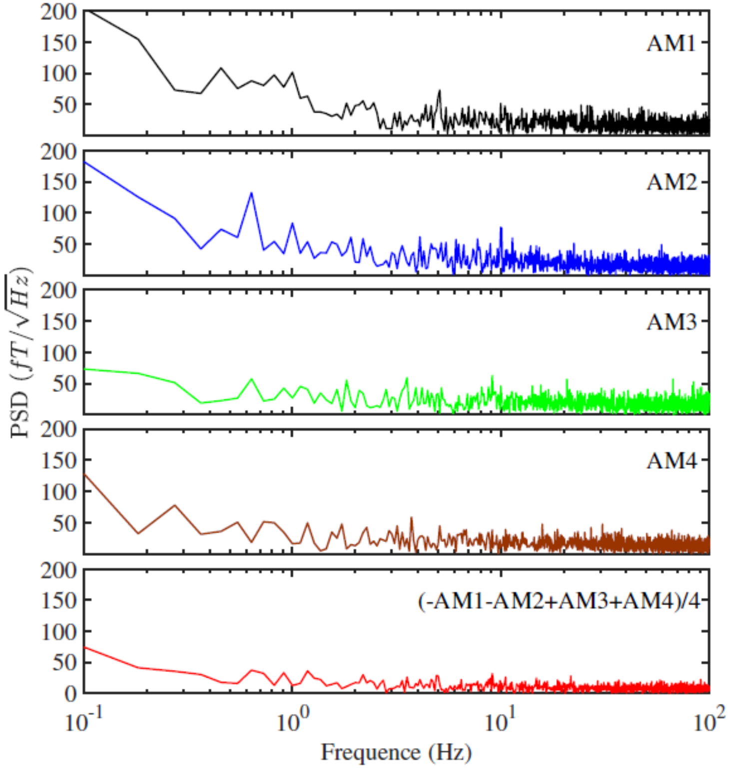


FIG. 2. Pulse examples of Phase A and C signals of the 3-phase encoder.



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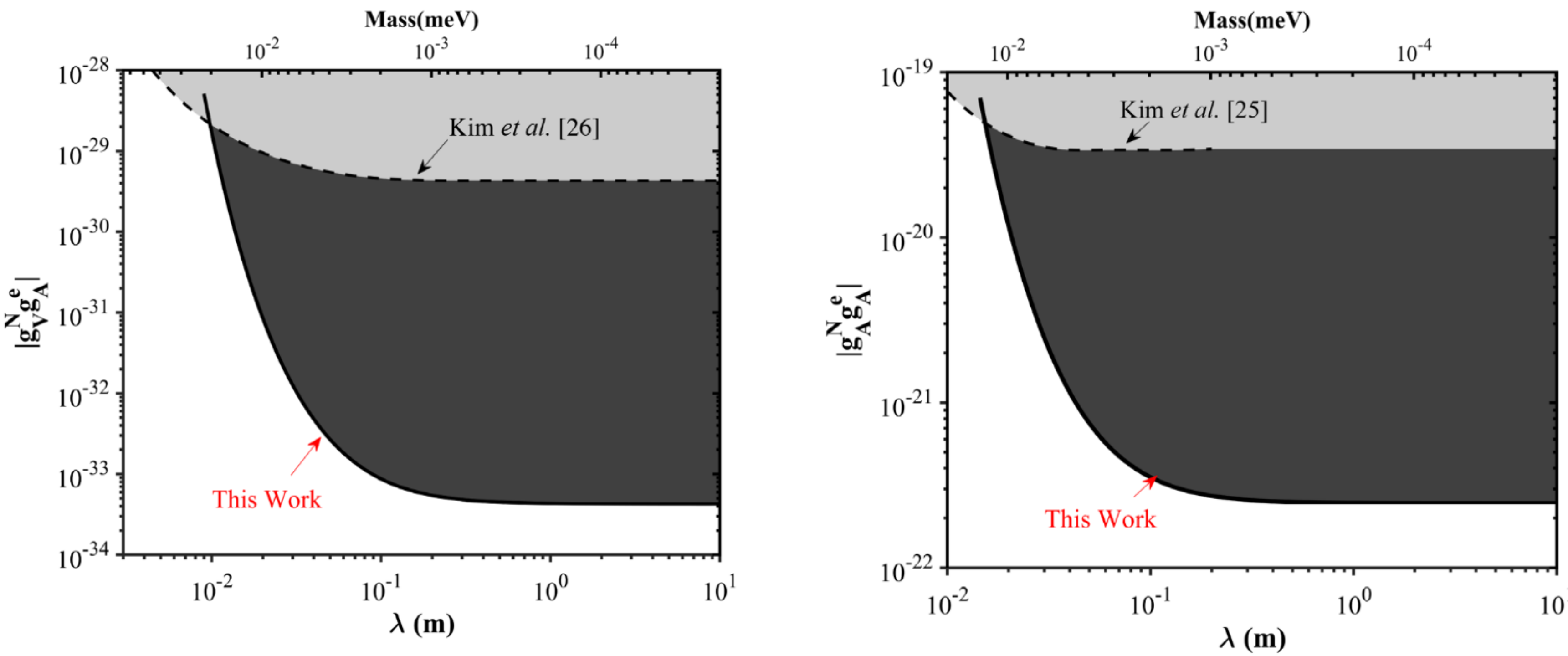
主要结果：



$$g_V^N g_A^e = 0.07 \pm 2.06(\text{stat}) \pm 0.07(\text{syst}) \times 10^{-34},$$

$$g_A^N g_A^e = -0.06 \pm 2.36(\text{stat}) \pm 0.08(\text{syst}) \times 10^{-22}.$$

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请批评指正！

谢谢