New Experimental Limit on the Electric Dipole Moment of the Neutron

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Symmetries

- **C and P symmetries are violated by weak interactions**

  normal matter (n,μ,π) readily breaks C and P symmetry.

- **The combination CP are different**

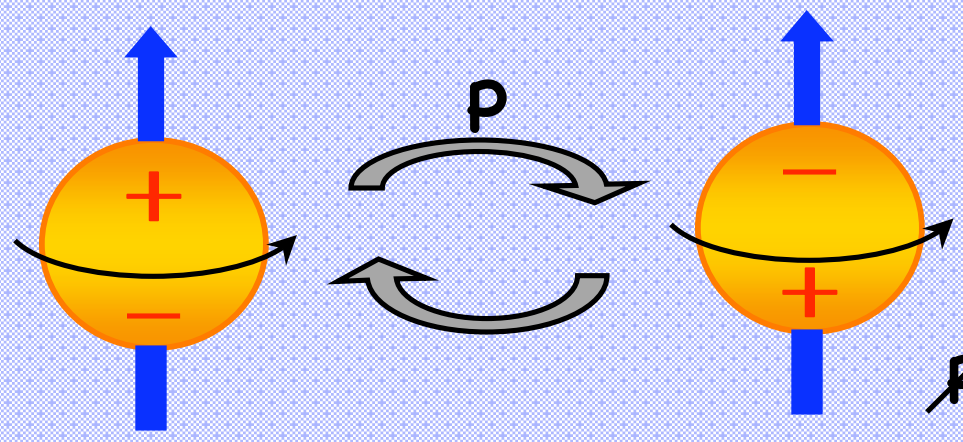
  normal matter respects CP symmetry to a very high degree.

- **Time reversal T is equivalent to CP (CPT theorem)**

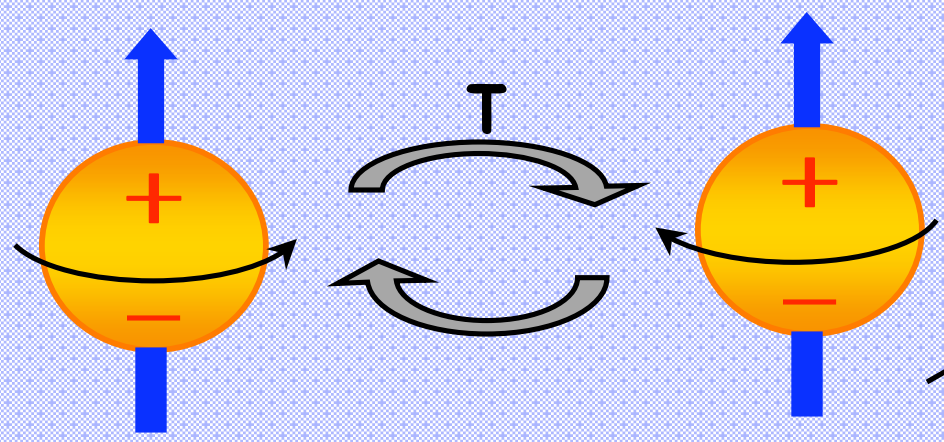
  normal matter respects T symmetry to a very high degree.

Electric Dipole Moment (EDM)

$$p = q \cdot d$$



~~P~~ no big deal



~~CP~~ big deal

The particle with EDM breaks P and T symmetry

Motivation

Measurement of EDM

Direct observation of T (CP)-symmetry

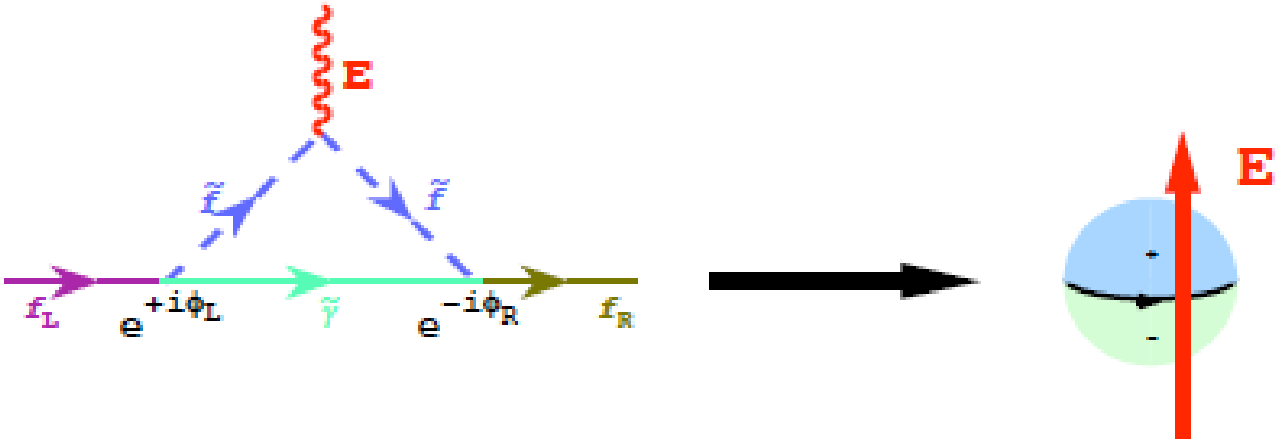
- EDM is effectively zero in SM
  CKM says neutron's EDM < 10^{-30} (e cm)

- EDM is big enough to measure in non-SM
  By assuming SUSY, neutron's EDM = 10^{-26}–10^{-28} (e cm)

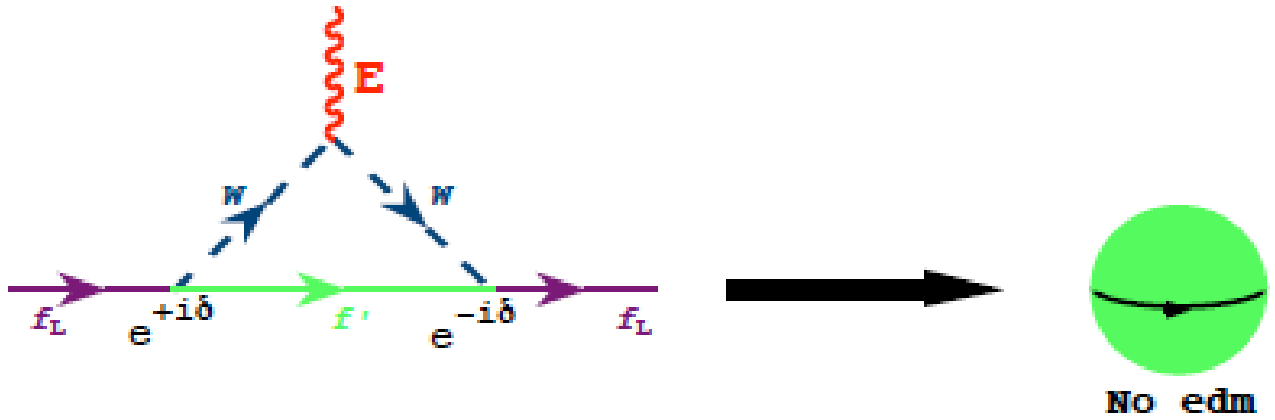
The measurement of EDM is the good probe to explore the Beyond SM

EDM in SUSY and SM

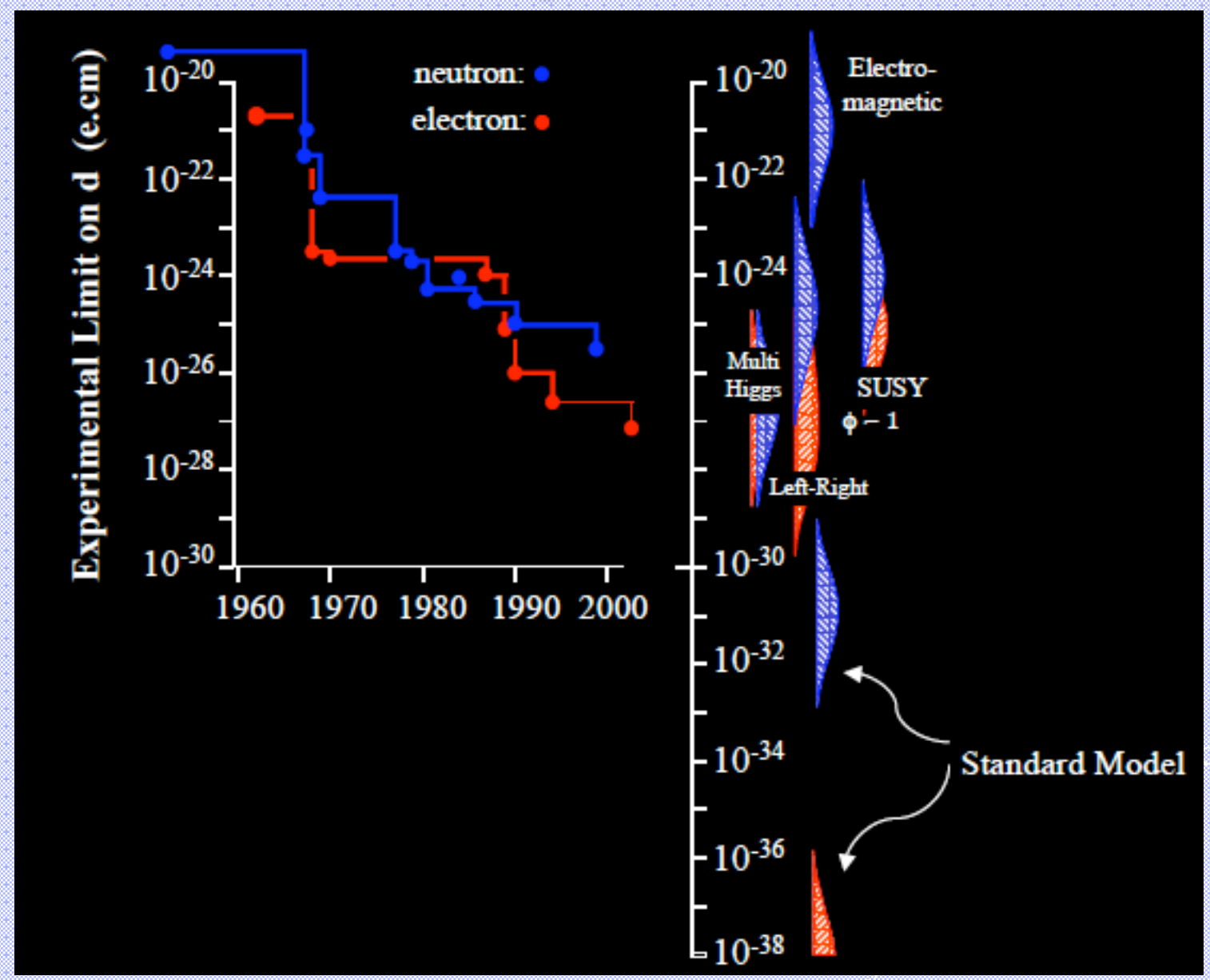
(a) SUSY: Generates edm in virtual cloud.



(b) Standard Model: Edm cancels.



History of EDM



ILL, Grenoble

60 MW reactor

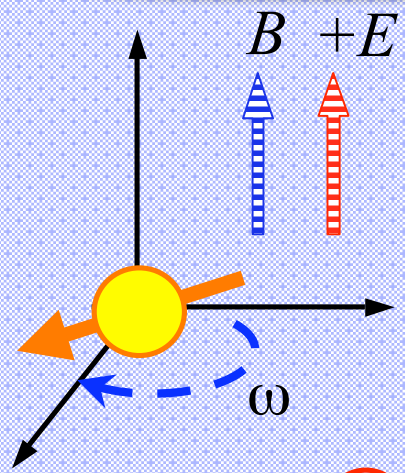
World's most intense source of neutrons for scientific research since 1973

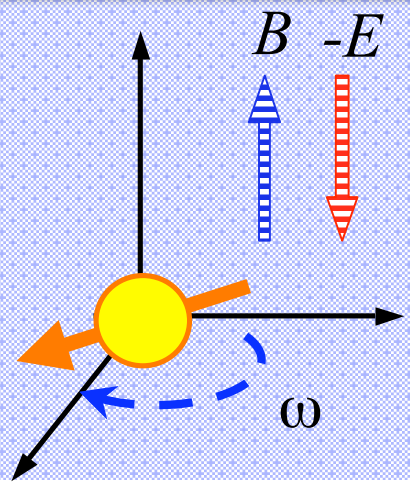
France, UK, Germany founding members

Measurement principle of EDM

The effect of EDM is observed using the Larmor precession

The precession of the magnetic moment
of the atomic nuclei about an external field





Larmor frequency

$$h\nu_{\uparrow\uparrow} = 2\boldsymbol{\mu}_n \cdot \mathbf{B} + 2\mathbf{d}_n \cdot \mathbf{E}$$

$$h\nu_{\uparrow\downarrow} = 2\boldsymbol{\mu}_n \cdot \mathbf{B} - 2\mathbf{d}_n \cdot \mathbf{E}$$

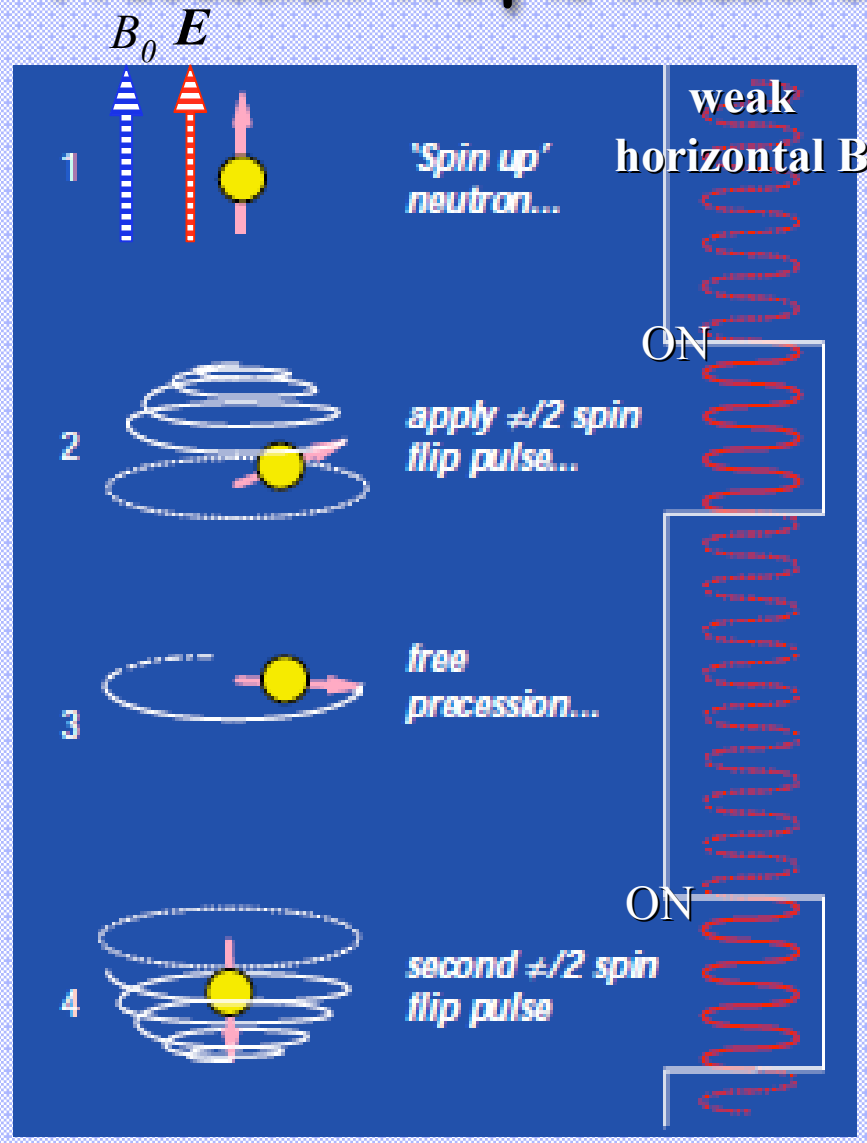
$$\Delta\nu = \nu_{\uparrow\downarrow} - \nu_{\downarrow\uparrow} = \frac{4dE}{h}$$

It's difficult to measure this with high precision

Ramsey resonance technique

Ramsey resonance technique

Precession freq is measured with high precision by this way



We set $f_B = \nu$

Larmor frequency : ν ⟶ $\frac{2\mu B}{h}$

B frequency : f_B

- $f_n = f_B$ (no EDM)

  Spin is tipped over by 4th step

  ⇒T symmetry is conserved

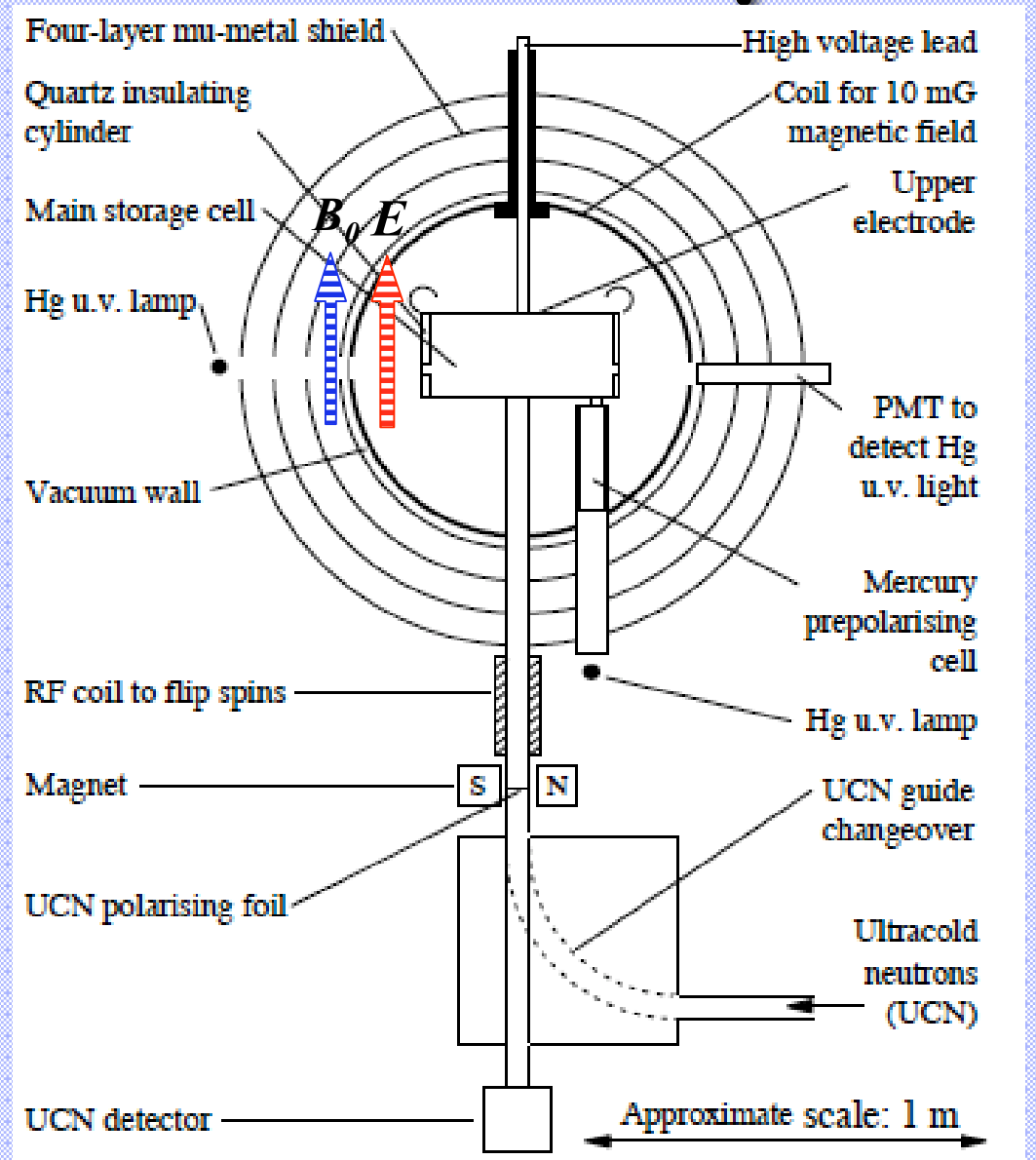
- $f_n \neq f_B$ (EDM)

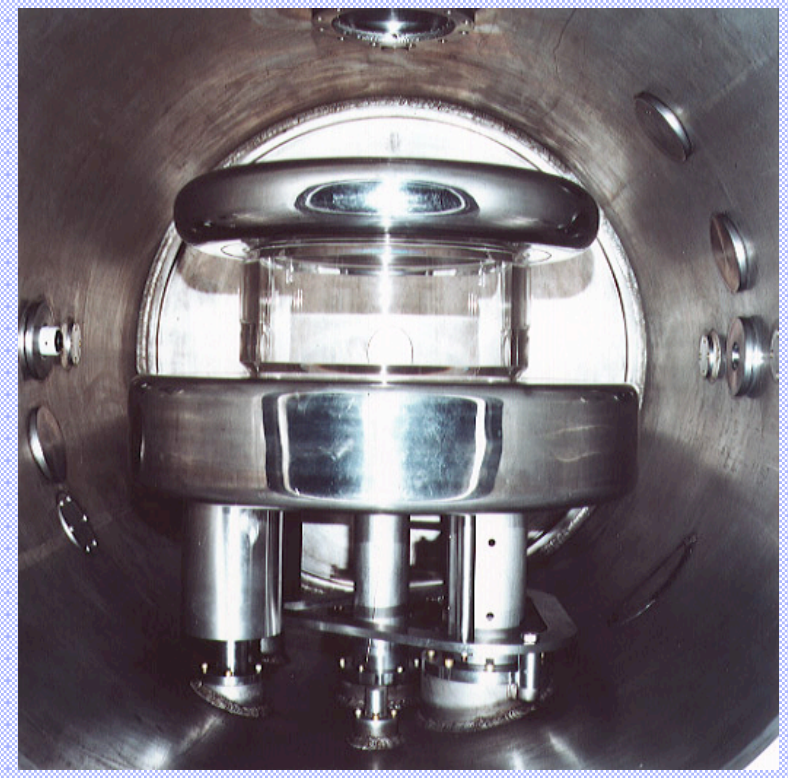
  Spin is NOT tipped over by 4th step

  ⇒T symmetry is NOT conserved

Count the number of upward and downward neutron!

Experiment



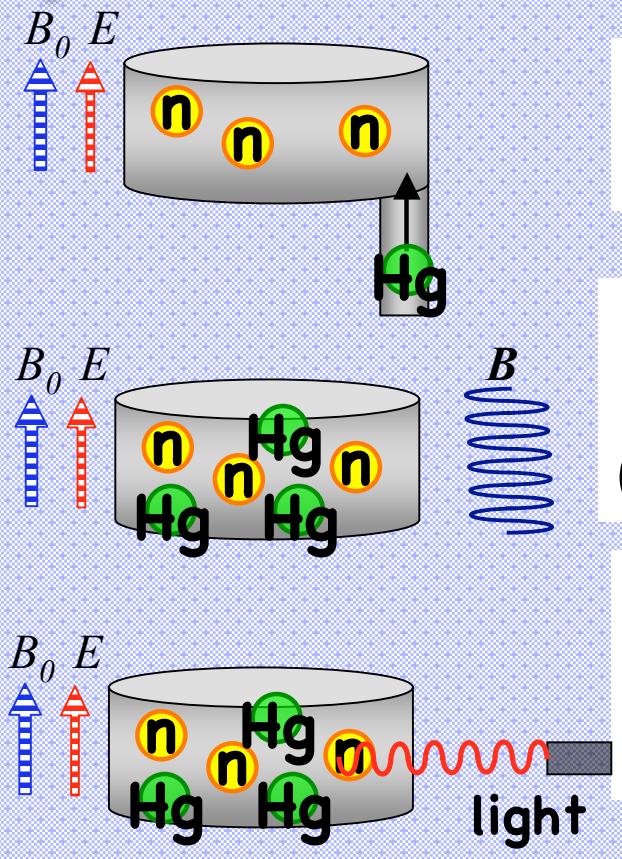


E = 4.5 kV/cm
B = 1 μT
T = 130 s

Hg co-magnetometer
(B is measured to 1pT)

Magnetometer

Systematic error on EDM experiment = Magnetic environment



1, Spin-polarized ^{199}Hg are enter the cell after neutron

2, A magnetic field (8Hz) is applied for a short period.
(the magnetic resonance frequency of ^{199}Hg)

3, The beam polarized light from ^{204}Hg transverse the cell and it's intensity is monitored.

The EDM of ^{199}Hg
< 8.7×10^{-28}ecm

The precession freq of ^{199}Hg is obtained
⇒ By $\omega=\gamma B_0$, B_0 is obtained

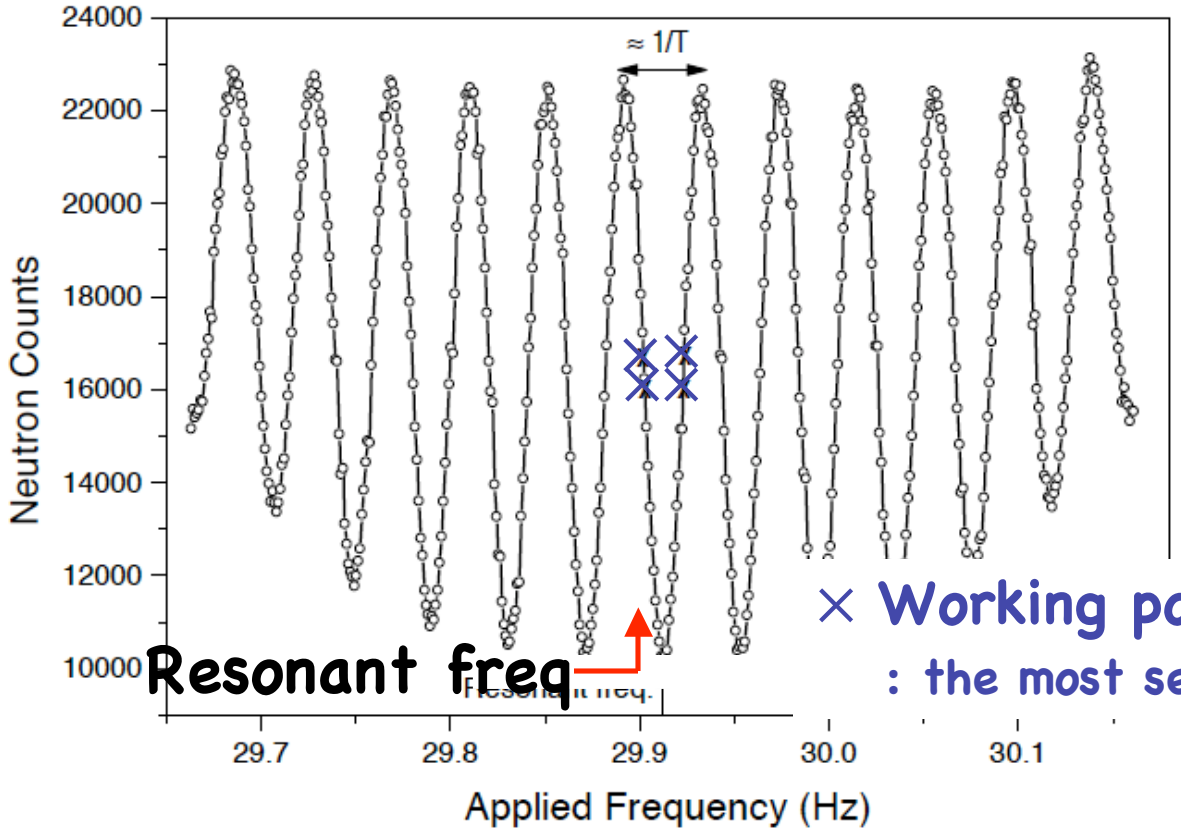
Neutron freq fitting

To get the freq of N, N count is fitted

Fit function

$$N = N_{\text{avg}}\left[1 \mp \alpha\cos\left(\frac{\Delta f_0}{\Delta\nu}\pi - \phi_{\text{avg}}\right)\right]$$

$$\Delta f_0 = f_0 - f_1$$



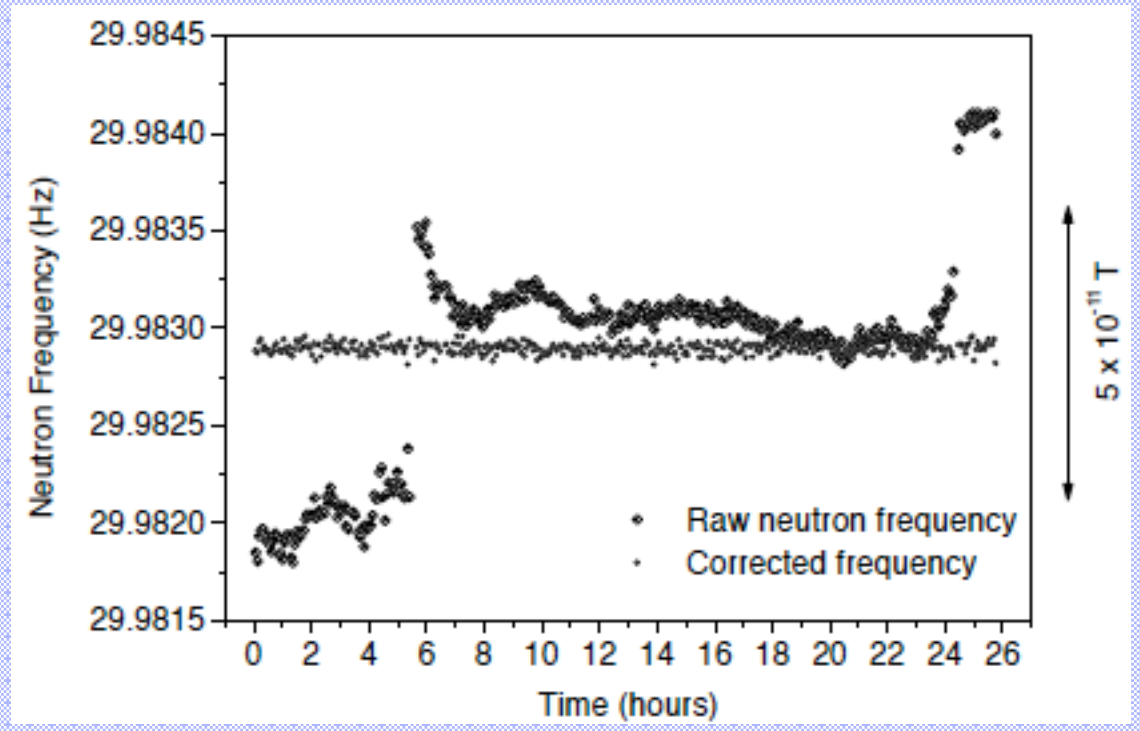
Resonant freq

× **Working points**

: the most sensitive area to freq

Neutron resonant freq

Neutron freq is corrected using the performance of magnetometer



$$\sigma_B = \frac{1}{\gamma_n 2\pi\alpha T\sqrt{N}}$$

→ 2 nG

$$\sigma_{d_n} \approx 10nG$$

Magnetic field drift has eliminated using magnetometer

Results

- The result of this experiment

$$d_n = 1.9 \pm 5.4 \times 10^{-26} e \text{ cm}$$

- The result included the previous data

$$d_n = [-3.4 \pm 3.9 \text{ (stat)} \pm 3.1 \text{ (syst)} \times 10^{-26}] e \text{ cm}$$

combined

$$d = \frac{1/\Delta d_1^2}{1/\Delta d_1^2 + 1/\Delta d_2^2} d_1 + \frac{1/\Delta d_2^2}{1/\Delta d_1^2 + 1/\Delta d_2^2} d_2$$

$$d_n = -1.0 \pm 3.6 \times 10^{-26} e \text{ cm}$$

Upper limit

$$|d_n| < 6.3 \times 10^{-26} e \text{ cm (90\% C.L.)}$$

Systematic error

- **Leakage currents and sparks**
  result in small additional magnetic field.
  → ∽ 1nA OK
- **Electrical activity**
  disturb the mercury to estimate a reliable freq.
  → The cycle is rejected
- **v×E effect**
  is below 1×10^{-26} ecm → OK
- **Other high-voltage induced effects**
  High voltage stack effects the precession freq of Hg and n.
  → Half of data were taken for each direction of B.
  → The difference is $(0.3\pm5.4)\times10^{-26}$ e cm

Conclusion

- The systematic error is reduced to negligible by the cohabiting magnetometer

- The upper limit of neutron EDM combined the previous data

$$|d_n| < 6.3 \times 10^{-26} e \text{ cm } (90\% \text{ C.L.})$$