SAKHAROV'S EXPLANATION OF THE ASYMMETRIC UNIVERSE AND THE SEARCH FOR THE NEUTRON ELECTRIC DIPOLE MOMENT

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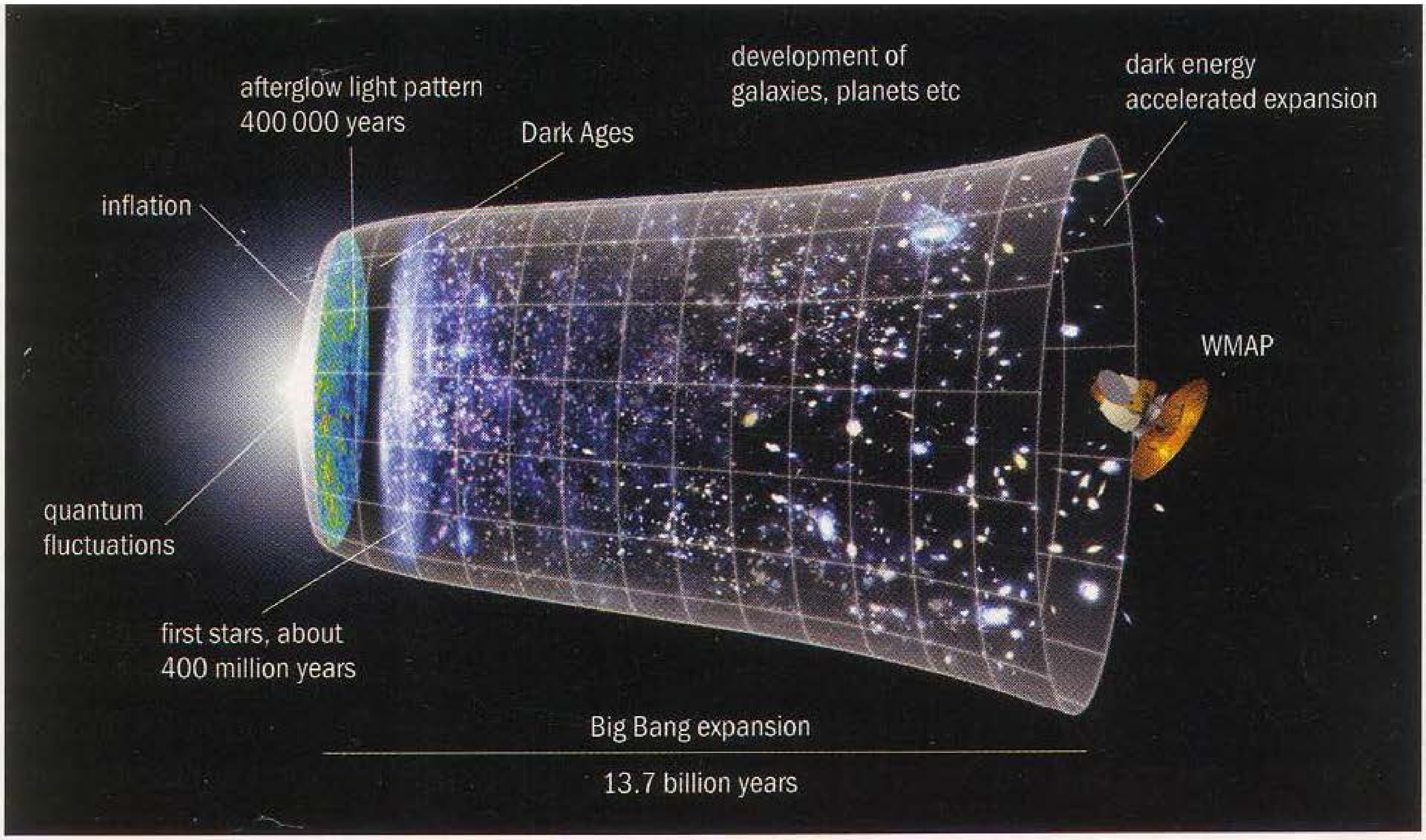
International Conference, 40 Years after Andrei Sakharov's *Reflections on Progress, Peaceful Coexistence and Intellectual Freedom:* Russia Yesterday, Today and Tomorrow. 24-25 October 2008. Cambridge, Mass. Panel 3: Sakharov the Physicist.



Timeline of the universe from the Big Bang to now. Rapid inflation during the first second was first proposed 25 years ago and is now supported by the new results from WMAP.

(WMAP = NASA'S Wilkinson Microwave Anisotropy Probe)

Universe:
Barionic Matter, 4%
Dark Matter, 23%
Dark Energy, 73%

From CERN Courier (May 2006) 12

The Universe is Fundamentally Asymmetric:

U = MATTER + ~~ANTI-MATTER~~

Sakharov's explanation (Sakharov's 3 conditions),

ЖЭТФ 5 (1), 32-35 (1967):

$U(t=0) = M + \overline{M}$

Then, at a very early stage, $t \sim 10^{-25}$ s,

1. ~~CP~~ (more than in the SM)
2. The conservation of N_b (the barion number) is only approximate.
3. The Universe is not stationary.

At present:

$$N_b / N_\gamma = 10^{-9}$$

$N_\gamma\ (t > 4x10^5 y) \approx N_{CMB}$ (cosmic microwave bgd)

$N_{CMB} \approx 400$ in cm^3.

In the past:

$$N_b = \overline{N}_b \sim N_\gamma$$

Without Sakharov's conditions,

it would be $N_b / N_{CMB} \sim 10^{-18}$

Why ~~CP~~ ?

First, ~~CP~~ means ~~T~~.

(we believe in CPT)

Second, ~~CP~~ leads to different reaction for particles and antiparticles.

Example

$$\frac{\Gamma(K_L^0\to\pi^-\ell^+\nu)-\Gamma(K_L^0\to\pi^+\ell^-\nu)}{\Gamma(K_L^0\to\pi^-\ell^+\nu)+\Gamma(K_L^0\to\pi^+\ell^-\nu)}=\delta\approx 0.003\neq 0$$

However,

the already known violations of the CP symmetry (explained in the SM) are NOT sufficient to explain the observed barion-antibarion asymmetry of the Universe. WE NEED A NEW PHYSICS!

Where can we look for that new physics?

LHC (CERN)

Higgs

Super-symmetric particles.

SUSY?

Super-strings?

EDM's

measurements with precision close to the SM limits.

$d_{n,SM} \sim 10^{-31} e\cdot cm$

$d_n, d_p, d_D, \ldots$

3 types of EDM's

1. Usual:

No correlation between $\vec{d}$ and $\vec{J}$.
No violations of T and P symmetries.
Can exist only in degenerate states.

Example: Hydrogen

$$\mathcal{E} = -\frac{me^4}{2\hbar^2(1+m/M)}\frac{1}{n^2}\ ;\ \ell = 0, 1, \ldots, n-1$$

$$\Delta\mathcal{E} = -\vec{d}\vec{E}\ ;\ d = n(n_1 - n_2).$$

Linear Stark

2. Induced:

Correlates with an external E-field.

Example: Deuteron

$$d_i = \alpha_{ik} E_k$$

$$\Delta\mathcal{E} = -\frac{1}{2}\alpha_{ik} E_i E_k \quad \text{(quadratic Stark)}$$

$$= -\frac{1}{2}\alpha_S E^2 - \frac{1}{2}\alpha_T \left[\underbrace{J_i J_k + J_k J_i - 4/3}_{=0 \text{ for protons, } S=1/2}\right] E_i E_k$$

3. Correlated with $\vec{J}$:

$$\vec{d} = \text{const} \cdot \vec{J}$$

We want to find this.

$\vec{d} = const \cdot \vec{J}$ violates T, P, CP

$$H = -\vec{\mu}\vec{B} - \vec{d}\vec{E}$$

T	P	
$t \to -t$	$\vec{x} \to -\vec{x}$	
$\vec{B} \to -\vec{B}$	$\vec{B} \to +\vec{B}$	(axial)
$\vec{E} \to +\vec{E}$	$\vec{E} \to -\vec{E}$	(polar)
$\vec{S} \to -\vec{S}$	$\vec{S} \to +\vec{S}$	
$\vec{v} \to -\vec{v}$	$\vec{v} \to -\vec{v}$	
$\vec{v}\times\vec{B} \to \vec{v}\times\vec{B}$	$\vec{v}\times\vec{B} \to -\vec{v}\times\vec{B}$	

$$H \to -\vec{\mu}\vec{B} + \vec{d}\vec{E}$$

$$\vec{\mu} = \frac{e\hbar}{2mc} g \vec{S}; \quad \vec{d} = \frac{e\hbar}{2mc} \eta \vec{S}$$

$\eta = 2\times 10^{-15}$ if $d = 10^{-29}$ e.cm

In the neutron edm, d_n, experiments, $\vec{B} \parallel \vec{E}$, and first $\vec{E}$ then $-\vec{E}$ are used. $d_n \propto (\omega_+ - \omega_-)$, Ramsey resonance freq's.

In our d_D, d_p, ... experiments, we will use (among other things) the $(t \to -t)$ imitation:

$\vec{v} \to -\vec{v}$, $\vec{B} \to -\vec{B}$, $\vec{E} \to \vec{E}$.

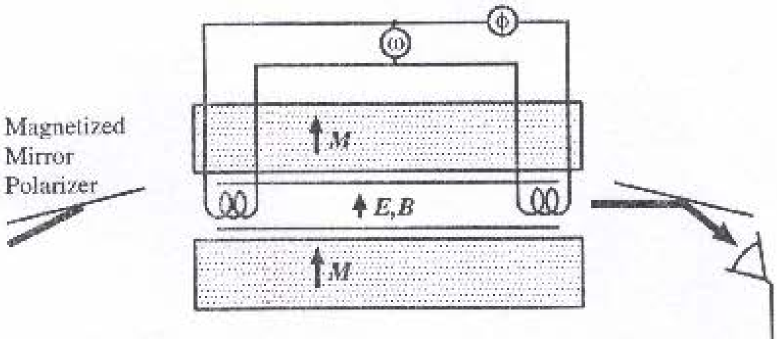
$d \propto (\omega_+ + \omega_-)$

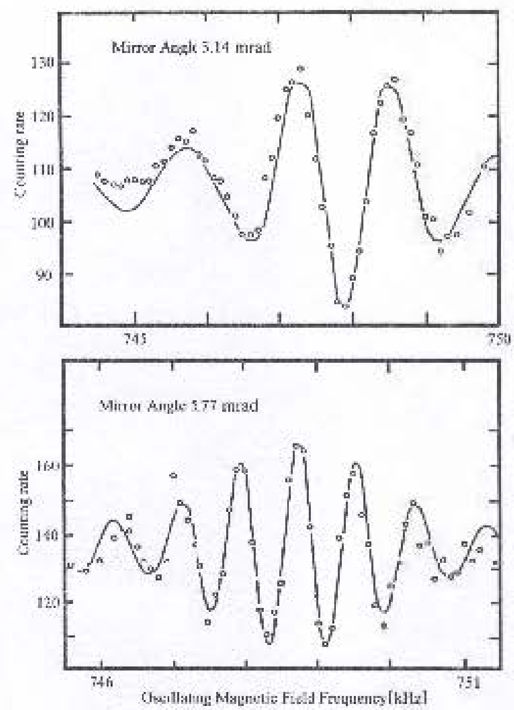
Neutron EDM Experiments

Neutron precession frequency will shift by $\Delta\omega = 2\vec{d}\cdot\vec{E}/\hbar$

(d = 10^{-26} e•cm, E = 10 KV/cm => 10^{-7} Hz shift)

Ramsey's Separated Oscillatory Field Method





Limitations:

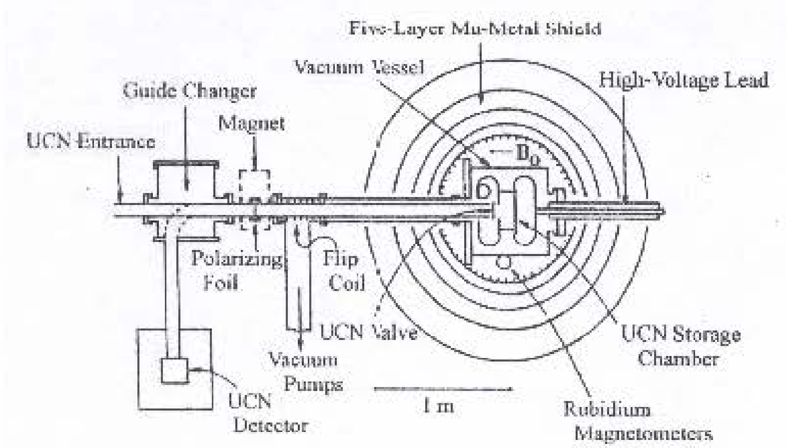
- Short duration for observing the precession
- Systematic error due to motional magnetic field (v x E)

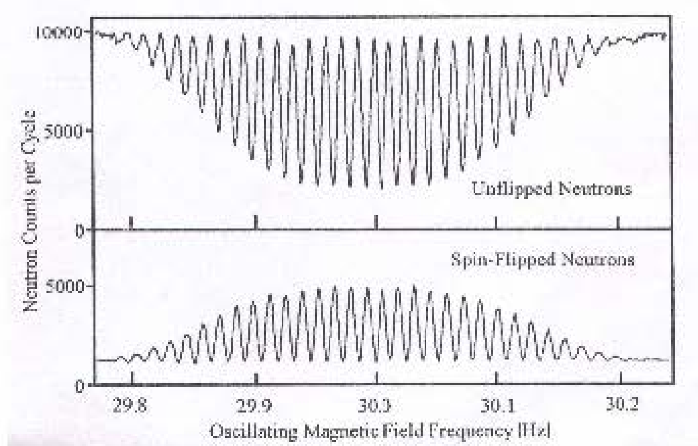
Both can be improved by using ultra-cold neutrons

From Jen-Chieh Peng's report, Cape Cod, 19-22 June, 2006

Neutron EDM Experiment with Ultra Cold Neutrons

ILL Measurement





- Use ^{199}Hg co-magnetometer to sample the variation of B-field in the UCN storage cell
- Limited by low UCN flux of ~ 5 UCN/cm^3

A higher UCN flux can be obtained by using the "superthermal" down-scattering process in superfluid He

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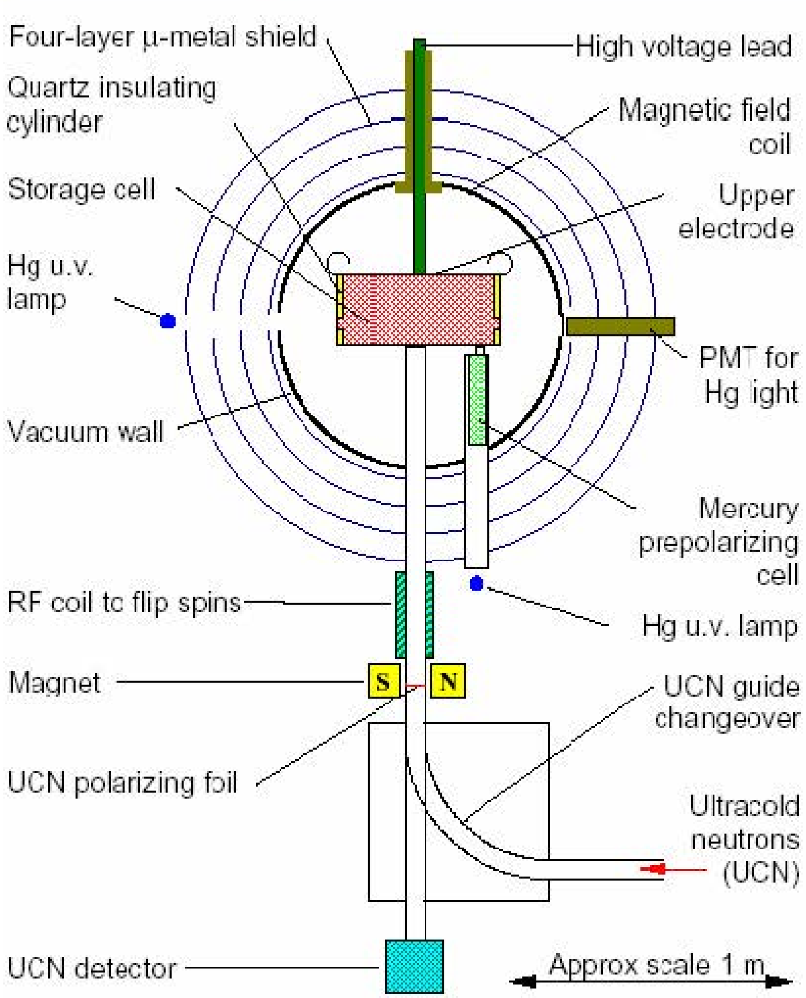
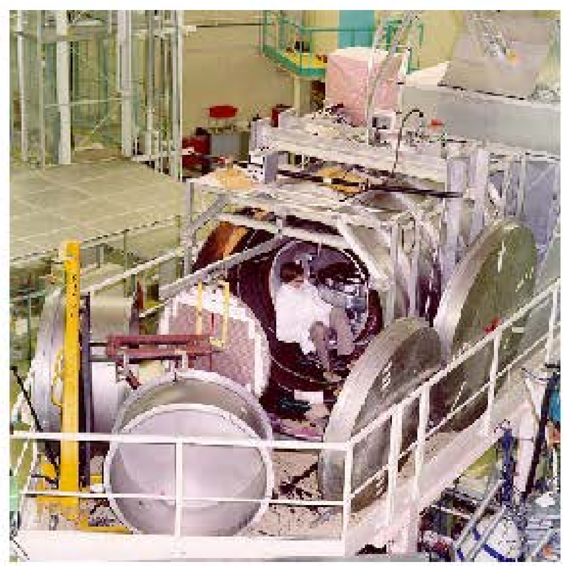


Context

Sussex-RAL-ILL experiment

$d_n < 3 \times 10^{-26}$ e cm

C. A. Baker et al., hep-ex/0602020
P. G. Harris et al., PRL 82 (1999) 904



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