Particle and Astrophysics: The neutrons perspective

Examples on why to use neutrons

Stephan Paul

Physik Department TUM

Overview

- The first 3 minutes of the Universe (in a nutshell)

- Weak interaction properties of hadrons
  - Neutron lifetime measurement
- Flavour diagonal CP-violation
  - EDM of the neutron
- Nature and the search for right-handed partners
  - Neutron bound β-decay

- Toolbox: Ultracold neutrons
  - Sources with D_2 converter
  - Sources with superfluid helium

- Summary

10^{-43} seconds:

The curtain is being lifted…

Space and time are foamlike….

<u>Superstrings:</u> a 'Weltformel' ?

- **All forces are unified**
- **The world is 10-dimensional**
- **However, only 4 dimensions have participated in the expansion of space All other dimensions are curled up**

History of the Universe

10^{-35} - 10^{-32} s:

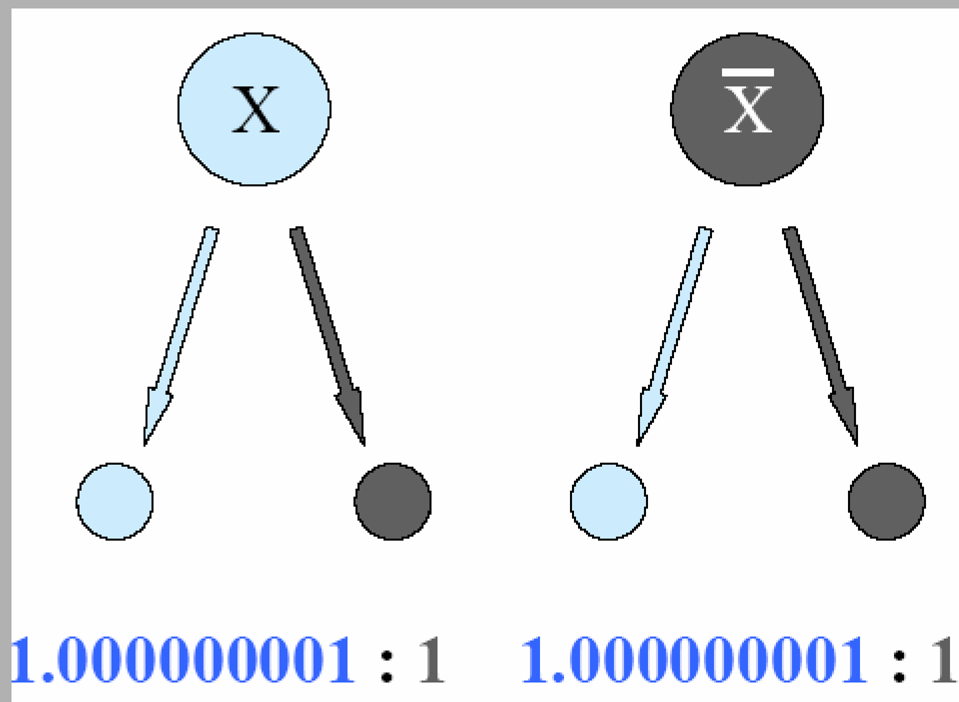
Inflation:

within 10^{-32} seconds space expands by a factor 10^{50}

- **Quantum-fluctuations in the energy density are being amplified (3 K background radiation)**
- **The build the base for future galaxy formation**

History of the Universe

A tiny excess of matter over antimatter is created



We are made from the 1 in the ninth decimal

History of the Universe

Until 10^{-10} seconds:

Soup from elementary particles and exchange bosons constantly interacting

Thereby cooling off by spatial expansion and modification of coupling strength

History of the Universe

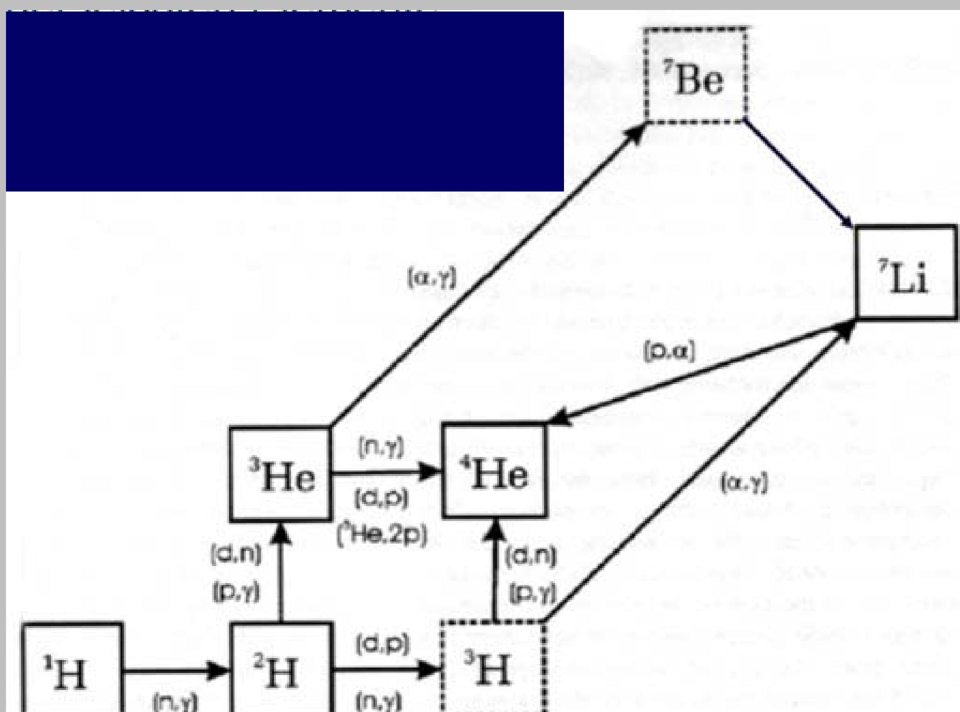
10^{-10}-10^{-6} seconds: Electroweak symmetry breaking

Neutrinos decouple:
Weak interaction is becoming too weak, neutrinos stop exchanging energy and momentum with other particles

History of the Universe

10^{-2}-10^{3} seconds:

Creation of first elements: Primordial nucleosynthesis



No stable elements with A=5, 8

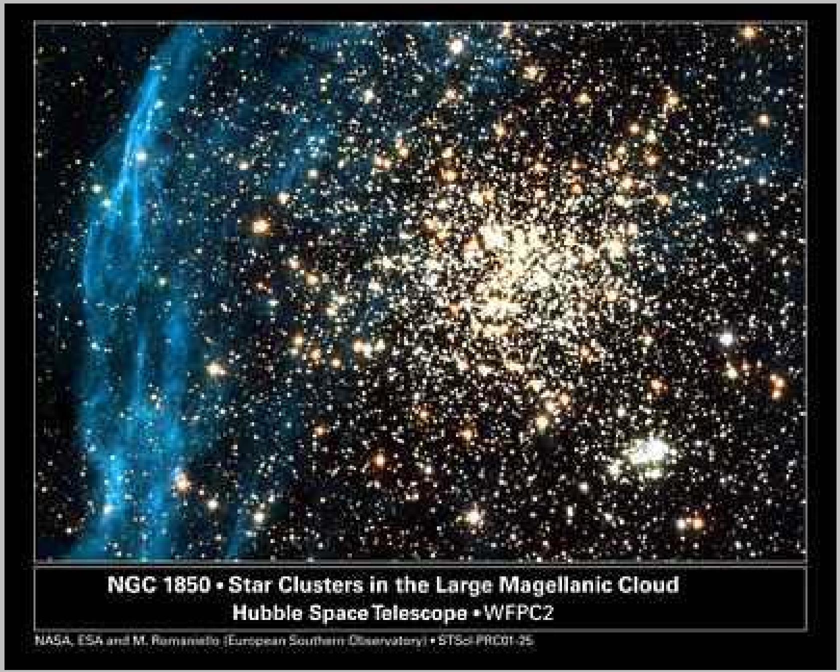
^{4}He is heaviest element

The first 3 minutes are over

History of the Universe

10^5 years:
Creation of atoms
Decoupling of photons

From 10^9 years on:
Creation of stars and galaxies



Neutron decay and BB-Nucleosynthesis

- < 1 second after Bing Bang:
  - Electroweak process: g_V, g_A
  - proton/neutron = 6:1, freeze out at $kT \sim \Delta m_{pn}$
- > 1second after Big Bang:
  - proton/neutron changes by n-decay to 7:1
- 100 seconds (kT = 0.1 MeV)
  - Deuteron formation
- Helium formation

$$p + e^- \longleftrightarrow n + \nu$$
$$n + e^+ \longleftrightarrow p + \bar{\nu}$$

$$n \longrightarrow p + e^- + \bar{\nu}$$

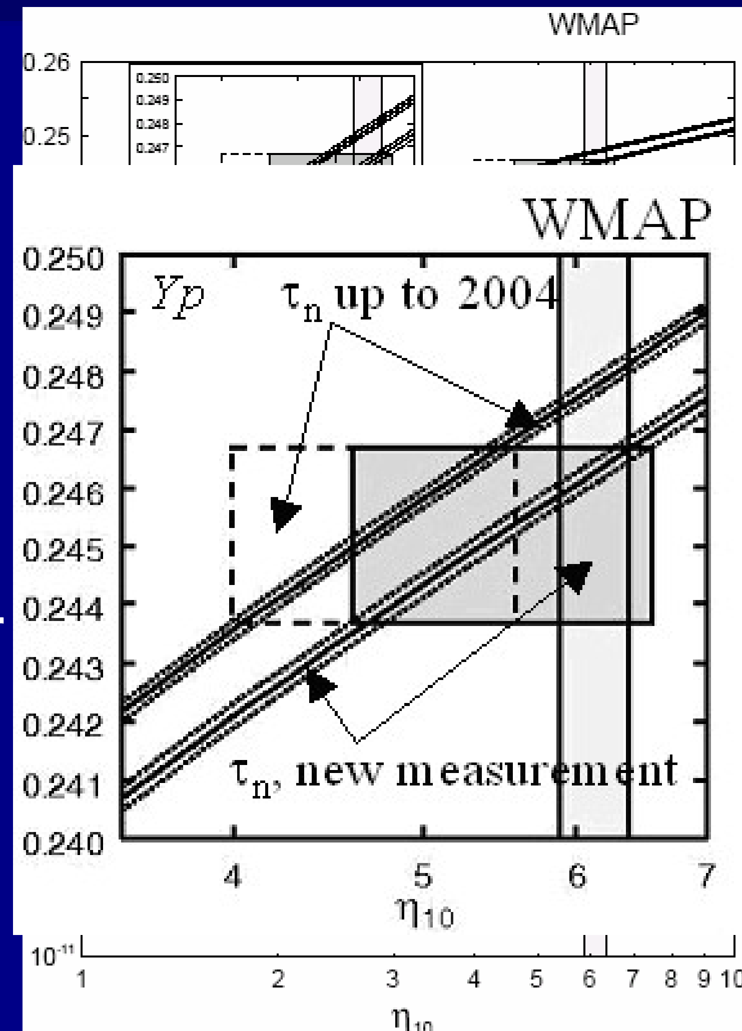
$$p + n \longleftrightarrow d + \gamma$$

$$d + n \longrightarrow H^3 + \gamma$$
$$H^3 + p \longrightarrow He^4 + \gamma$$
$$d + p \longrightarrow He^3 + \gamma$$
$$He^3 + n \longrightarrow He^4 + \gamma$$

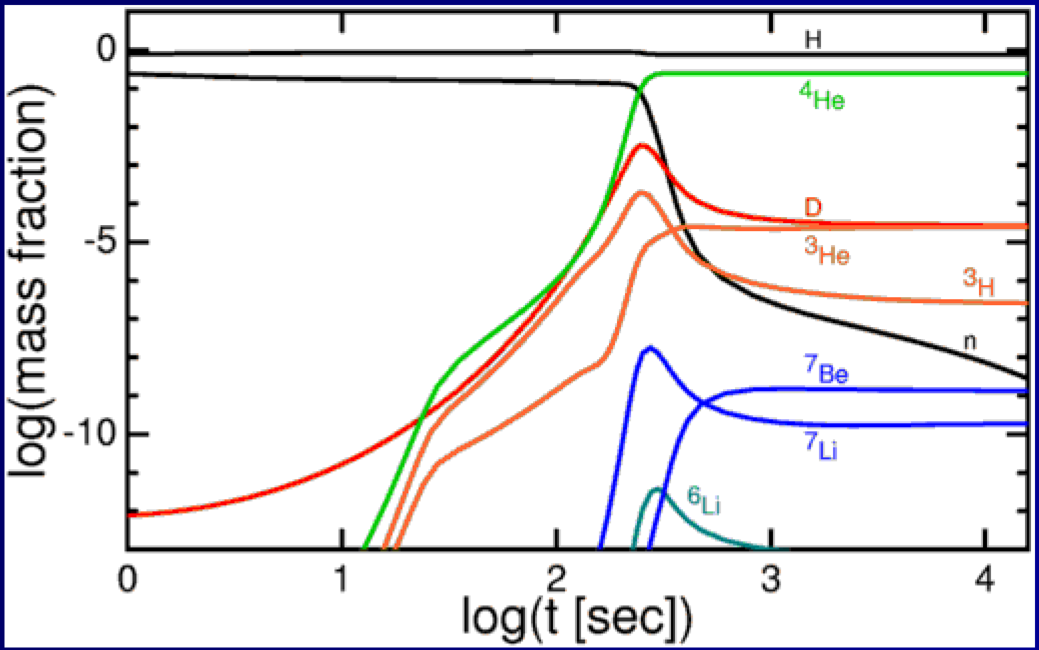
$$d + d \longrightarrow He^4 + \gamma$$
$$d + d \longrightarrow H^3 + p$$
$$H^3 + d \longrightarrow He^4 + n$$
$$He^3 + d \longrightarrow He^4 + p$$

Neutron lifetime and Cosmology

- Three parameters:
  - $\eta_{10} = (n_B / n_\gamma) * 10^{10}$
    - WMAP
  - Y_p = He / p
    - Metal-poor stars/galaxies
  - τ_n
    - Experiments
- Using standard weak/nuclear physics codes
  - Deuteron abundance (small)
  - Helium abundance
  - Lithium abundance (small)



Primordial Nucleosynthesis



Element generation as function of time

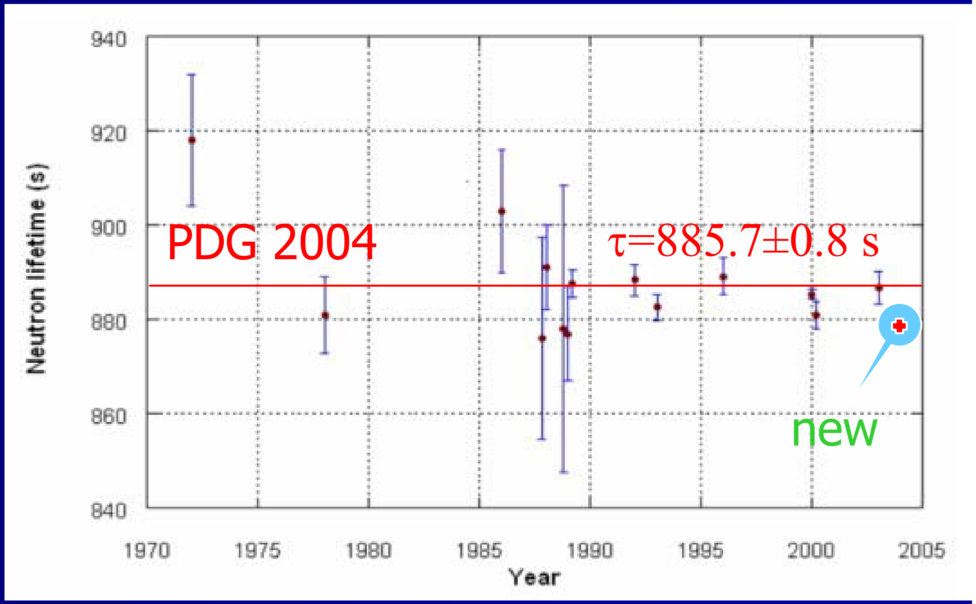
Current status of results

- Lifetime τ : $\tau_n \propto \frac{1}{g_V^2\left(1+3\lambda^2\right)}$ *with* $\lambda \coloneqq \frac{g_A}{g_V}$
- Current type of Experiments
  - In beam experiments - count decays in fiducial volume
  - Storage experiments - count decays after a preset storage time t
    - Storage losses
    - Loss of time information
- Present values

$$\lambda = -1.2695 \pm 0.0029$$

$$\tau_n = 885.7 \pm 0.8\ s$$

[PDG 2006]

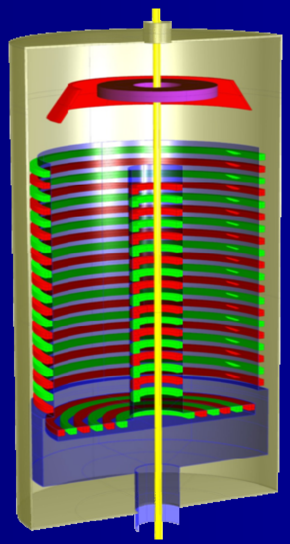


Measurement of the Lifetime

- A new lifetime experiment
  - High statistics (large volume)
  - Minimize systematic effects
    - No wall losses (no material walls)
    - Detection of surviving n after storage time t
    - Online detection of decay-protons
  - Detect defects
    - Depolarized neutrons
    - Vary spring tension
- Magnetic bottle for UCN

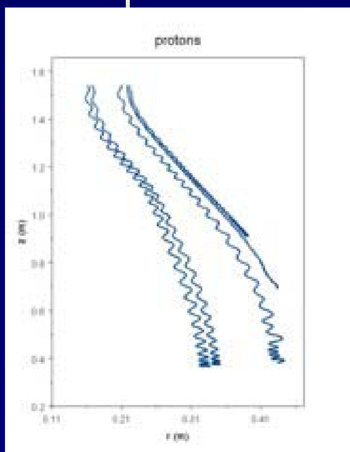
$$F = -\nabla(\mu \cdot B)$$

  - μ_n = - 60.3 neV/T
  - B_{max} = 2 T
  - attraction for $\vec{\mu} \| \vec{B}$

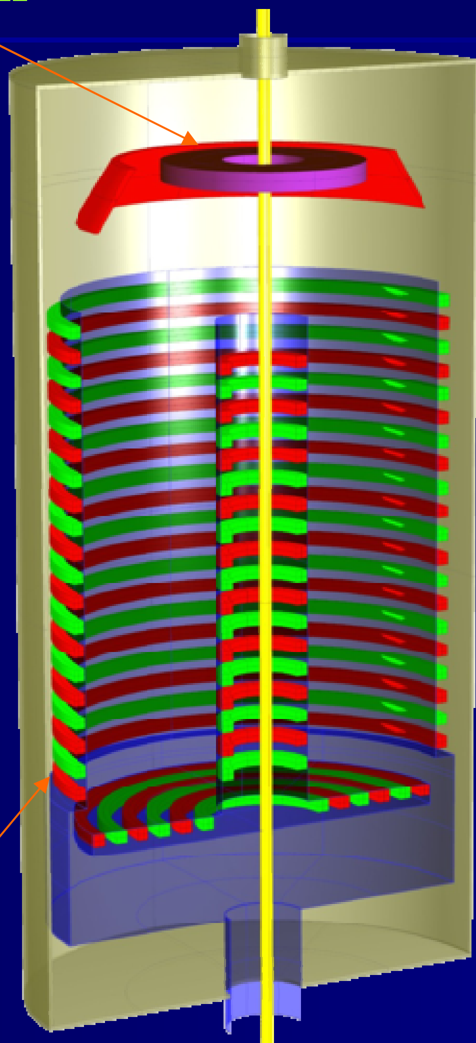


Experimental setup

Proton detection

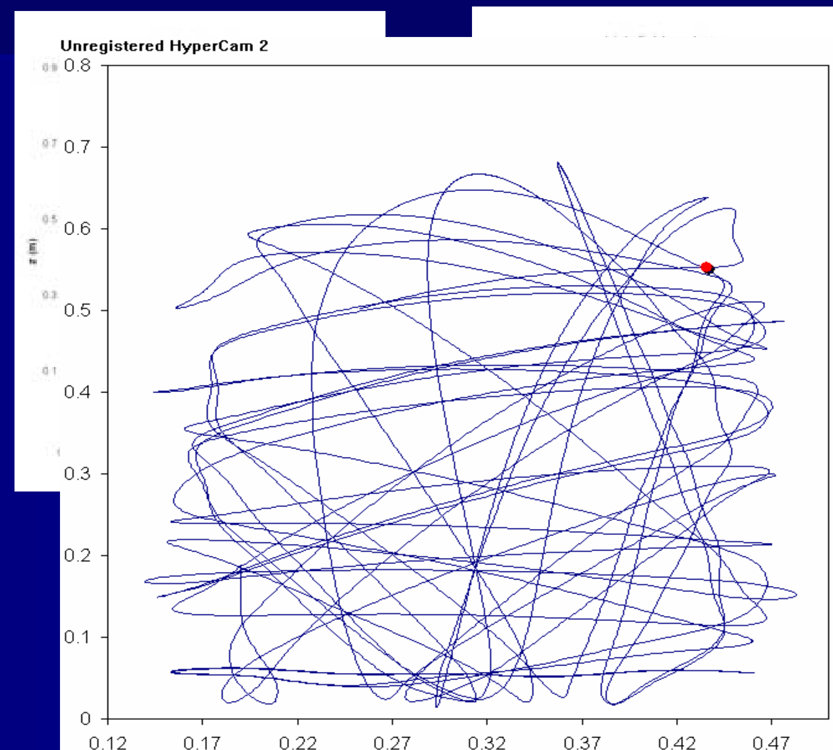


Proton trajectories

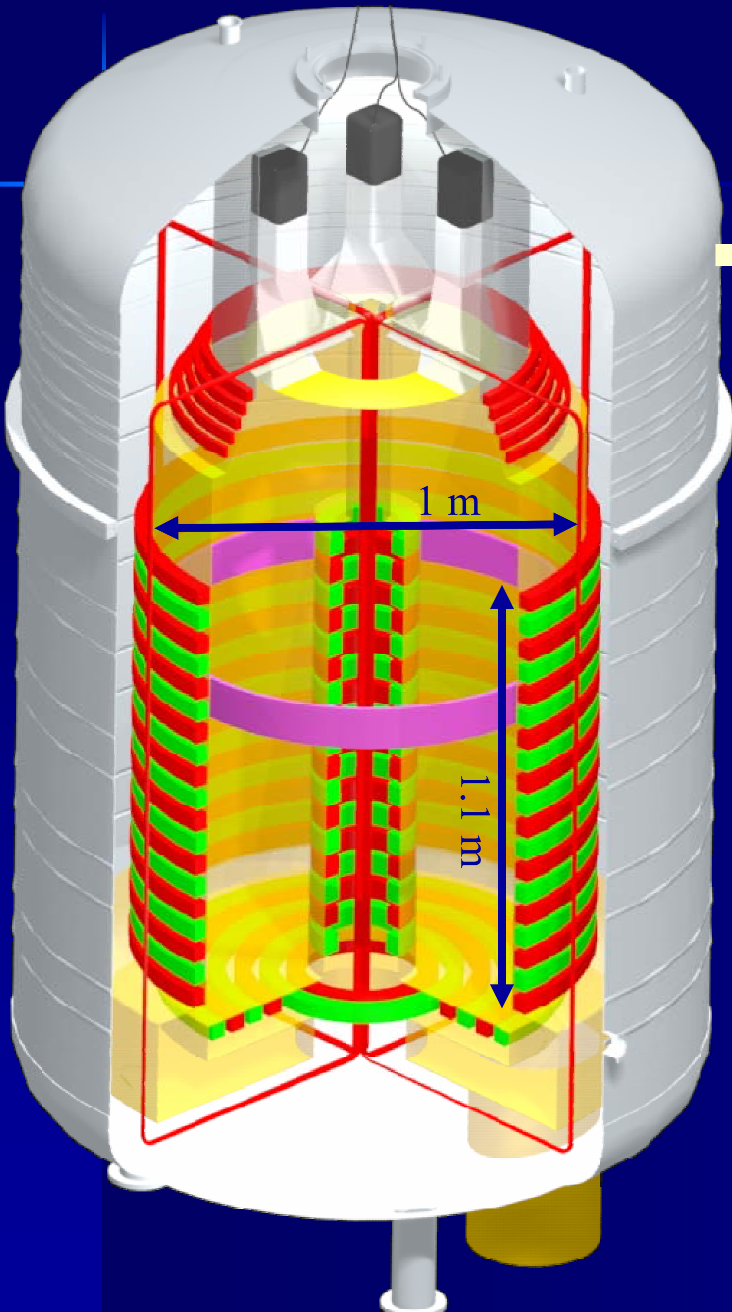


Magnetic multipole $B_{eff} \sim 2T$

Current rod



Design

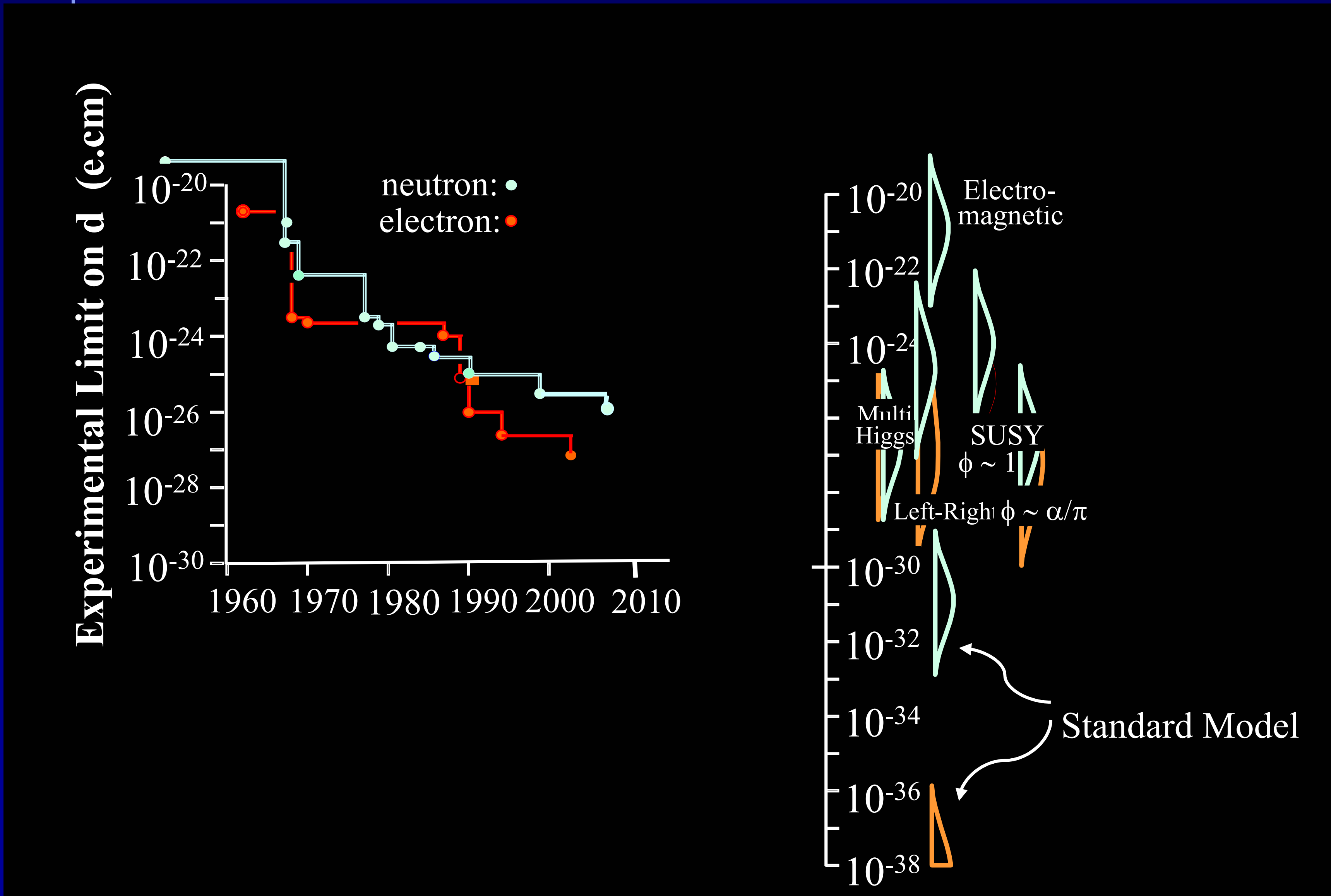


- Assume: new high-density UCN source (FRMII, PSI)
  - UCN (gas-) density: r = 10^3-10^4 cm^{-3}
  - B_{max}= 2 T B_{min}= 10-3 T
  - Volume: 700 l
  - N_{stored} = 10^7 -10^8
  - Statistical accuracy:
    - $\Delta t \sim 1s$ per measurement cycle (30 min):
    - $\Delta t \sim 0.1s$ in 2-4 days

CP-violation and EDM

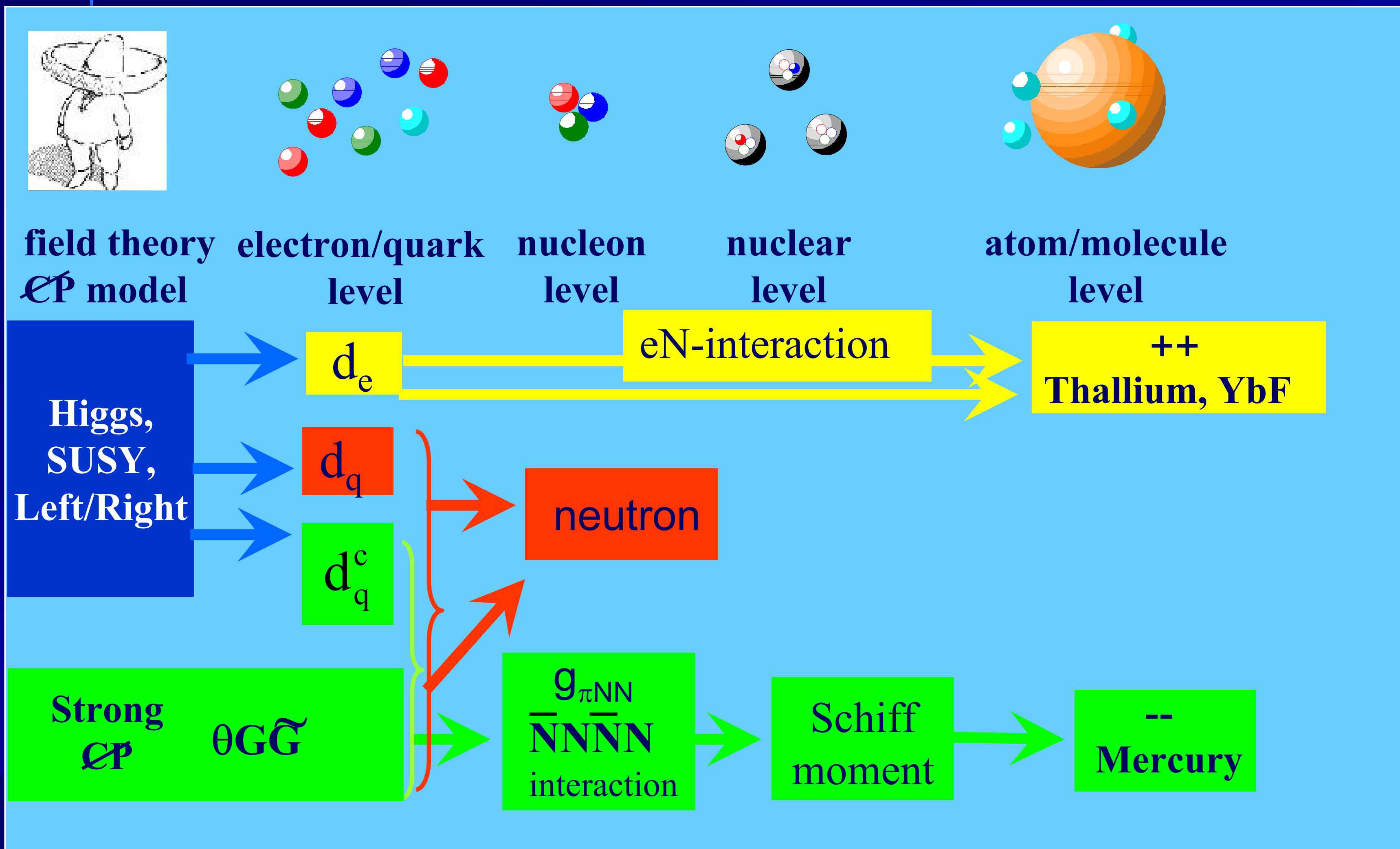
- EDM is a test for flavour diagonal ~~CP~~
  - Test of structure of vacuum at small distance scales
  - Background free probe for 'new physics' (unlike CKM induced ~~CP~~)
- CP violation in nucleons (neutron) needed for
  - Baryogenesis problem (matter vs. antimatter in the universe)
    - Cosmological requirement (Sakharov criteria)
    - Inflationary scenario suggests dynamical generation of baryon number
  - Test CP violating part in QCD (θ-term)
    - Magically fine-tuned to zero
- EDM can be studied in
  - Diamagnetic atoms
  - Paramagnetic atoms, molecules (~~CP~~ inducing electron-EDM d_e)
  - Neutron (~~CP~~ in quark sector)

Search for Electric Dipole Moments



Electric Dipole Moments and Physics

$\not{C}\not{P}$ from particles to atoms (main connections)

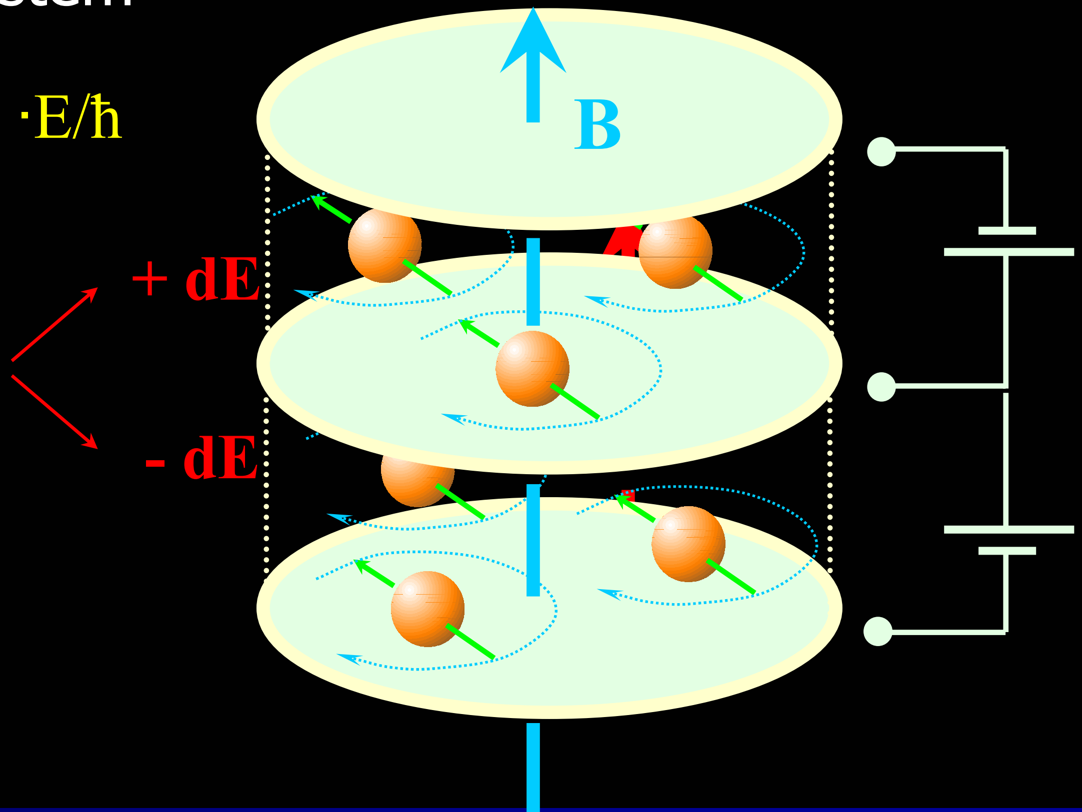


How to measure an EDM

- Ramsey method (split oscillatory fields)
- Two-chamber system

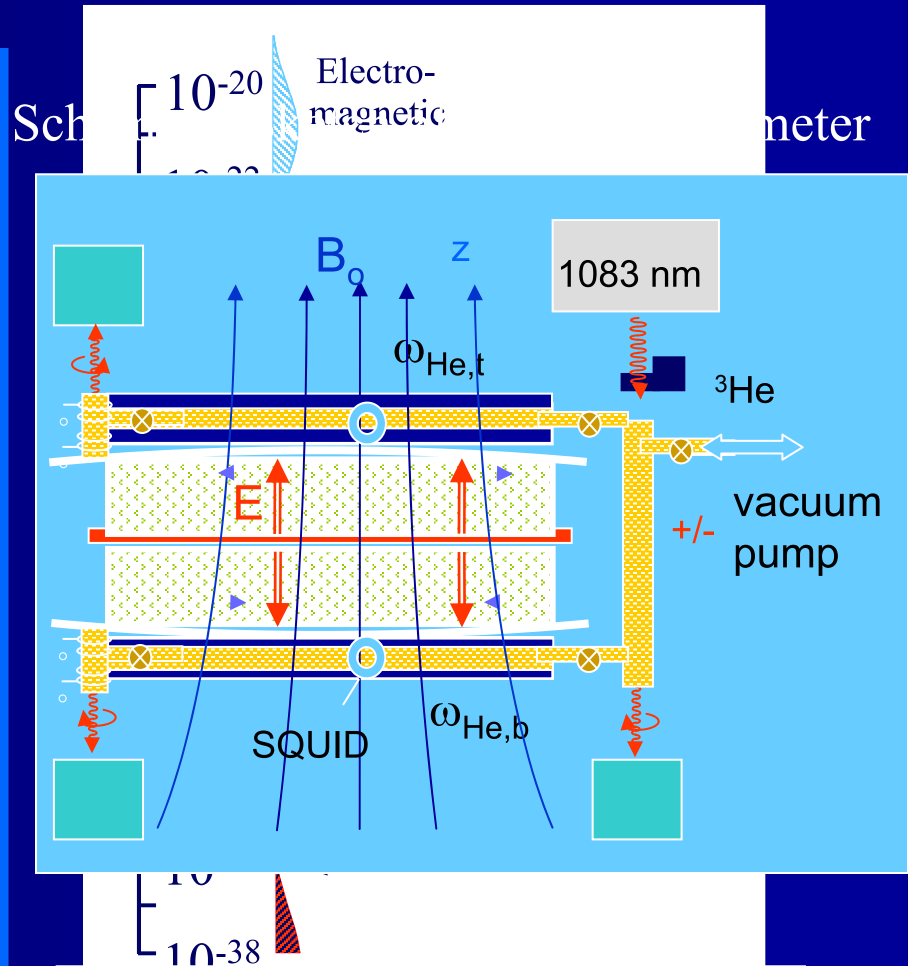
$$\Delta\omega = \omega_{\uparrow\uparrow} - \omega_{\uparrow\downarrow} = 4 \cdot d_n \cdot E/\hbar$$

$$h\omega = \pm \mu B$$



Measurement Accuracy

- Present limit: $d_n<3\cdot10^{-26}$ e·cm
- Limitations for δd_n:
  - – # stored neutrons
    - New UCN source (e.g. FRMII)
  - – E-field strength
    - New material for storage bottle
  - – B-field stability (10fT)/uniformity (3pT/cm)
    - New magnetometry (^{3}He)
    - shielding
  - – Systematic correlations
    - Field shapes, simulations
- Aim: d_n ✁ 10^{-27} e·cm (first round limit)
- Final aim: d_n✁10^{-28} e·cm



$$\sigma_\upsilon = 6.5\cdot10^{-8}\ Hz \quad \delta B = \sigma_\upsilon / \gamma_{He} \approx 2\ fT$$

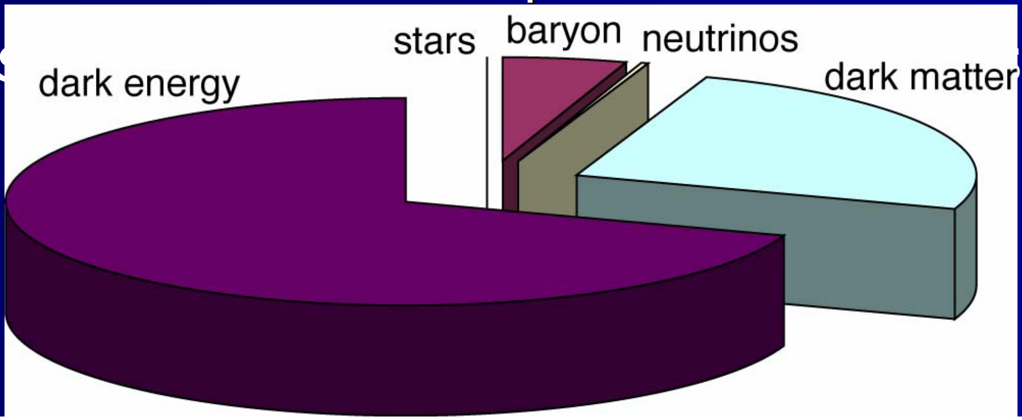
$$\left(\langle\omega_{t,He}\rangle - \langle\omega_{b,He}\rangle\right) \square \left\langle \partial B/\partial z \right\rangle$$

Competition

- Much efforts around the world with different approaches
  - Cryo-EDM at Grenoble (ILL) - super-thermal ^4He source with internal experiment
  - Lamoreaux/Golub in USA (NIST/LANL) - super-thermal ^4He, internal ^3He magnetometer, n-detection… very ambitious and difficult)
  - EDM in Switzerland (PSI) – (multi-cell system)
  - EDM at FRMII – ($\delta B \sim 2$ft) ! (Mainz – TUM – Gatchina)
- All efforts aim at similar accuracy ($d_n = 10^{-28}$ e·cm)
  - Different source techniques
  - Different magnetometry
  - Different systematic effects

Right Handed Neutrinos

- Observation of Neutrino oscillations requires neutrino mass
- Popular scenario:
  - light left-handed neutrinos
  - heavy right-handed neutrinos
  - Seesaw mechanism
- Implications on cosmology
  - Neutrino decay as source for Leptogenesis and CP violation
  - Candidate for dark matter particles
- What i ... ector ?



The Structure of Weak Interaction

- Standard (V-A) structure of weak interaction embedded in $SU(2)_L$
- Extensio[illegible]
  - Right handed currents (left-right symmetric models)
    - W_R, ν_R
    - Measure left-handedness of the ν
  - Tensor or scalar forces
    - g_T, g_S
    - Measure ratio of (V-A) coupling strength and total strength
- Use neu[illegible] $\vec{\sigma}_p$ [illegible] $\vec{\sigma}_e$ [illegible] $\vec{\sigma}_p$ [illegible] $\vec{\sigma}_e$ [illegible] $\cdot \vec{\sigma}_{\bar{\nu}_e}$
  - $n \to p e \bar{\nu}_e$ [illegible] $H \bar{\nu}_e$ with HFS analysis
  - Small branching fraction (BR=4·10^{-6}) (83% 1S, 10% 2S)

Helicity of Neutrinos*

M. Goldhaber, L. Grodzins, and A. W. Sunyar
Brookhaven National Laboratory, Upton, New York

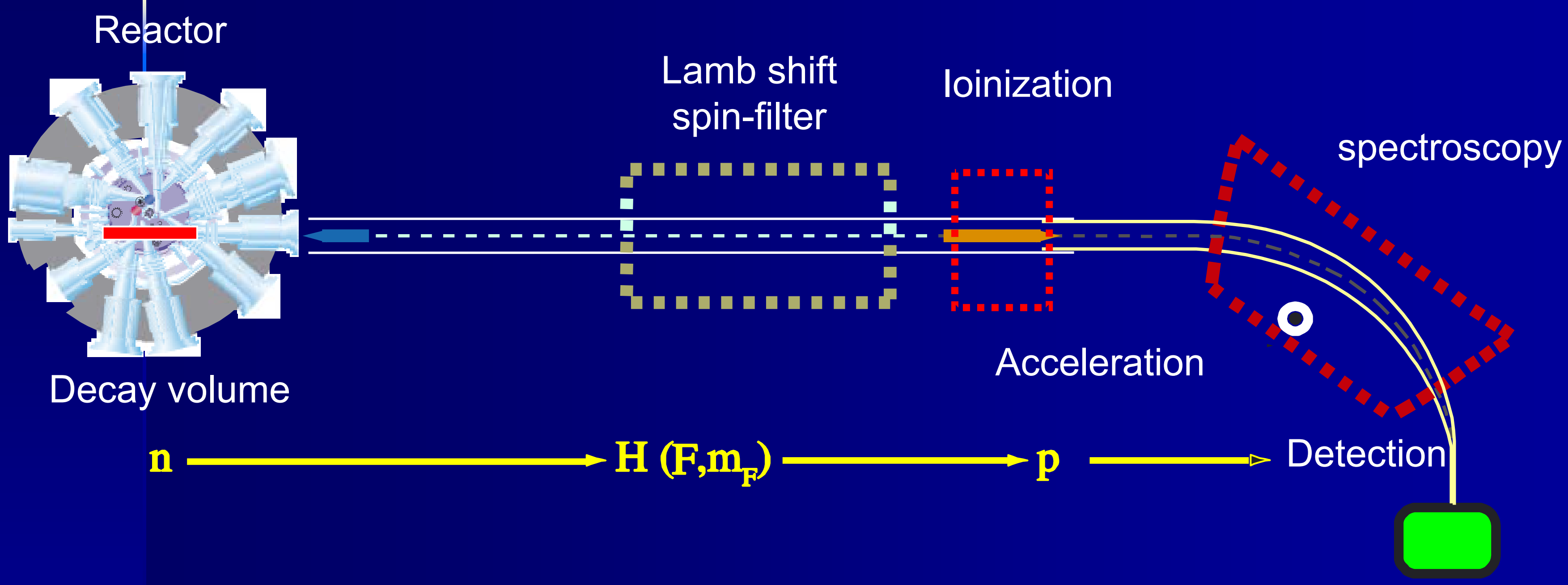
(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme, we find that the neutrino is "left-handed," i.e., $\sigma_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).

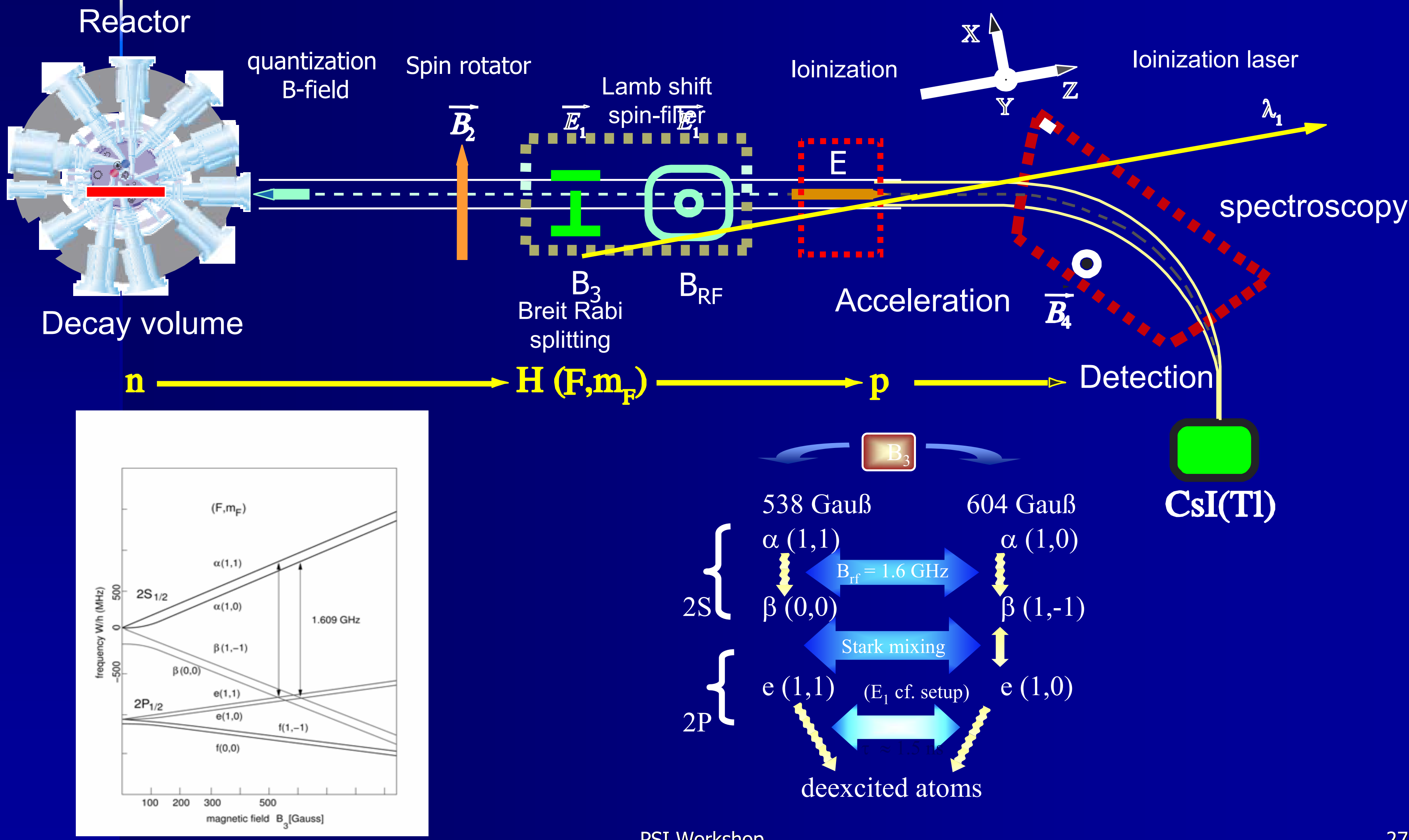
Measurement Technique

- Unpolarized n decay in magnetic field within reactor tube
  - $\vec{p}(H) = -\vec{p}(\bar{\nu}_e)$ with $|E^{H}_{kin}| = 326.5$ eV
  - $, \; _H = \frac{\vec{\sigma} \cdot \vec{p}}{|\vec{\sigma}| \cdot |\vec{p}|} = 0, \; , \; _{\bar{\nu}_e}$
  - Select F, m_F of emerging hydrogen atom using spin-filter method
  - Identify hydrogen from n-decay via
    - Doppler shifted laser-ionisation process
    - Magnetic spectroscopy
  - Rate: 0.3 H-atom/s in 2s-state
- Physics:
  - Relative rates of F=0,1, m_F=0,1 give signature for g_S and g_T
  - Rate of F=1, m_F= -1 shows (V+A)

Experimental setup



Experimental setup



Precision and Competition

- Precision expected:
  - Improvement on g_S upper limit: factor 10 in 2 days/ε (ε=efficiency)
    - Present accuracy: $|g_s/g_V| < 0.067$*
  - Improvement on g_T upper limit: factor 20 in 2 days/ε
    - Present accuracy: $|g_T/g_A| < 0.09$*
    - Improvement on [illegible]$_\nu$: factor 100 in 30 days/ε (statistically)
    - Present accuracy: 15% from μ,τ decays
- Competition
  - Neutron decay correlations
  - Direct searches for W_R at LHC
  - Muon and tau decay (Michel parameter) – presently best limit

*Severijns et al. 2006: global fit w/o τ_n^{new}

Working Plan n Bound–β-Decay

- Principle: Hydrogen spectroscopy at a reactor
- First stage (2007-2010):
  - Laboratory test A
    - Laser ionization of hydrogen with
    - Magnetic spectroscopy
    - Use H-source partially existing

$$|E^{H}_{kin}| = 326.5 \text{ eV}$$

I. Measurement: Detect neutron bound β-decay (FRMII)

- Second stage:
  - Laboratory test B
    - Test spin-filter method
    - Need polarized H source (second spin filter ?)

II. Measurement of HFS population

- Setup of high power IR laser (deexcite nS states with n > 3)

III. Measurement of HFS population related to [illegible]$_{\nu}$

Production of Ultra Cold Neutrons

Reactor Neutrons : E_0 = ~ 2 MeV

↓

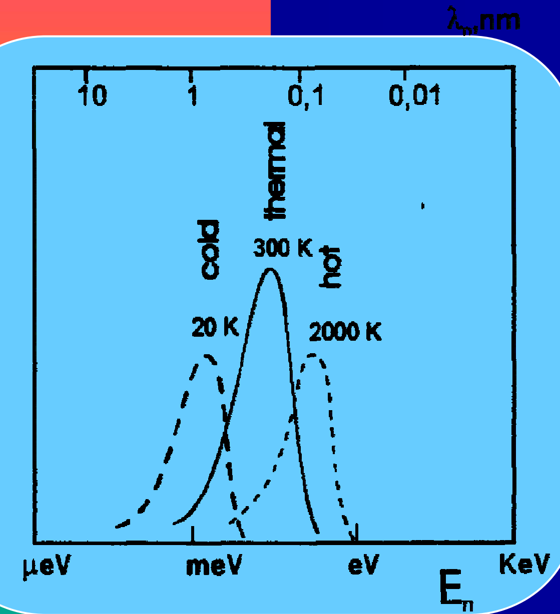
Moderator (heavy water) T = 300K
thermal neutrons E_0 = 25 meV

↓ **in or close to reactor core:**

Moderator (Deuterium) T = 20 K
cold E_0 = 4 meV

↓

Maxwellian velocity distribution::



↓

Selection and further cooling

Very cold (VCN)	$E_0 = 10^{-5}$ - 10^{-6} eV	**50-15 m/s**
ultracold (UCN)	$E_0 = 10^{-7}$ eV	**5 m/s**

Superthermal sources

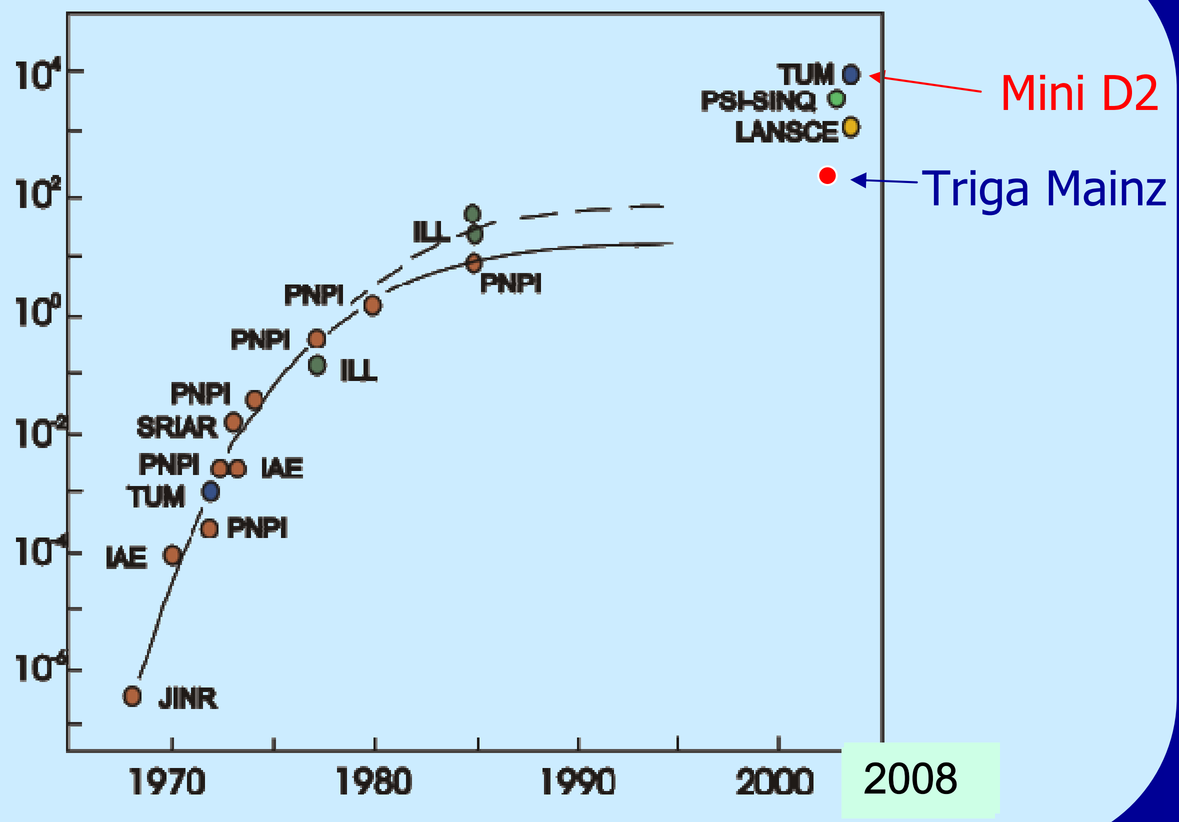
- Two systems are known for production of UCN (non-equilibrium cooling)
  - Solid deuterium
    - Upscattering processes < downscattering process
    - At T~5K: $\sigma_{absorption} \sim \sigma_{upscattering}$
    - Mean free path of UCN in solid D_2 ~ 10-15cm
    - Placement in cold beam w/wo premoderation
    - Position: close to n-source
    - Accumulation mode
  - Superfluid helium
    - No upscattering or absorption
    - Usable cold neutron flux for $\lambda \sim 8$Å
    - Placement outside strong heat input
    - Typically used for internal experiments
    - Extraction recently demonstrated

Examples of UCN sources

- Solid D_2- sources:
  - LANL
  - TRIGA (Mainz)
    - Using TUM geometry/prototype: 100,000 UCN detected in one ‘shot’
    - Upgrade in preparation
  - PSI (in preparation)
  - FRMII (financing now ok)

- Superfluid helium
  - NIST source (built-in lifetime experiment)
  - ILL: Cryo-EDM (built-in EDM experiment)
  - Small ‘portable’ test source at FRMII – allows extraction

UCN sources



TUM
PSI-SINQ
LANSCE
Mini D2
Triga Mainz
ILL
PNPI
PNPI
PNPI
ILL
PNPI
SRIAR
PNPI
IAE
TUM
PNPI
IAE
JINR
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
1970
1980
1990
2000
2008

Summary

- Neutrons offer excellent laboratory to study particle physics and cosmology
  - CP-violation and matter-antimatter asymmetry
  - Nucleon weak interaction and primordial nucleosynthesis
  - Right-handed part of nature – dark matter candidates
- Some key experiments performed with stored neutrons
  - Technological development of UCN sources
  - Large financial investment based on existing n-sources
  - Technological challenges
- Precision experiments required
  - Systematic and statistical accuracy mandatory
  - New ideas coming up – exploration stage