PARTICLE
ELECTRIC DIPOLE MOMENTS

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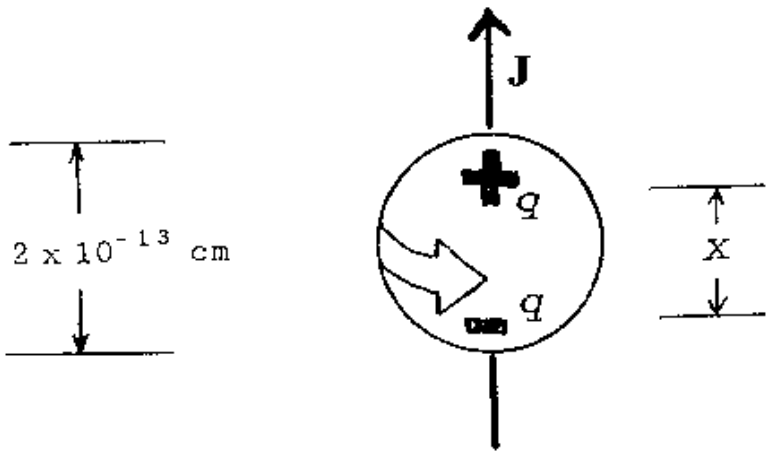
FINITE permanent EDMs require CP violation



$$d_n = q\,x$$

$$d_n = (1/(J+1)\,\Sigma\, q_i \mathbf{r}_i \cdot \mathbf{J}$$

If the symmetry CPT is conserved as is required for quantum field theory and for Lorenz invariance then $\not{T}$ and $\not{CP}$ always occur together

thus

$\not{T}$ implies $\not{CP}$

and vice versa

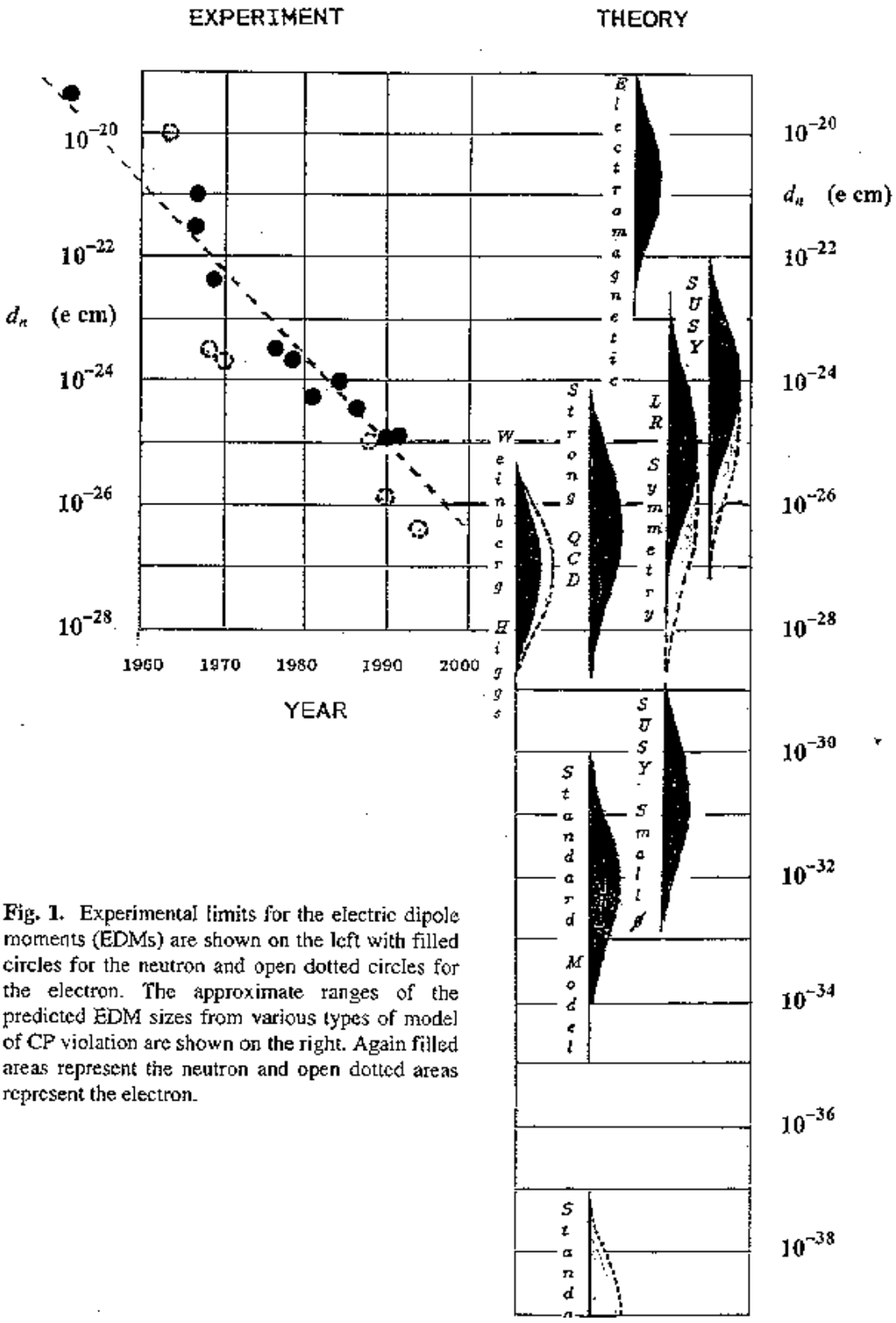
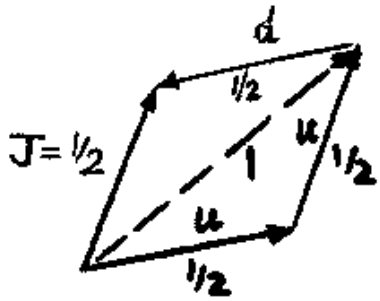


Fig. 1. Experimental limits for the electric dipole moments (EDMs) are shown on the left with filled circles for the neutron and open dotted circles for the electron. The approximate ranges of the predicted EDM sizes from various types of model of CP violation are shown on the right. Again filled areas represent the neutron and open dotted areas represent the electron.

SOME BACKGROUND POINTS

- **Naive quark model of the neutron**



whence

$$d_n = (4/3)d_d - (1/3)d_u$$

or $$d_n \approx (4/3)d_d$$

- **Current view of the spin structure of the neutron**
  From EMC and SMC experiments and some hyperon data
  Ellis, J and Flores, R A (CERN-TH/96-18) quote

$$d_n = (0.82 \pm 0.03)d_d - (0.44 \pm 0.03)d_u - (0.11 \pm 0.03)d_s$$

In examining the this result we need another fact-

- **Fundamental Fermion (e μ d u ...) EDMs**
  In several models of CP violation e.g.
  Supersymmetry, LR-symmetry, Weinberg multiple Higgs,
  [see Barr, S M *Int J Mod Phys A* **8** (1993) 209] the results for d take the form

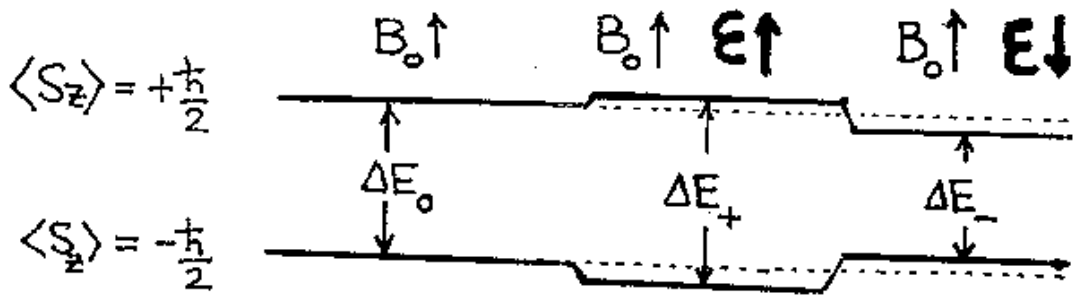
$$d_i = K\, m_i Q_i$$

Can produce significant cancellation

whence

$$(d_d/d_e) = (m_d/m_e)(Q_d/Q_e) \approx 10$$

MEASUREMENT PRINCIPLE
for the electric dipole moment d
(for any $J = 1/2$ "atom")



The associated Larmor spin precession frequencies ν_n are:

$$\nu_n(0) = \Delta E_0/h = -2B_0\mu/h$$

$$\nu_n(+) = \Delta E_+/h = \left[-2B_0\mu - 2\mathcal{E}d_n\right]/h$$

$$\nu_n(-) = \Delta E_-/h = \left[-2B_0\mu + 2\mathcal{E}d_n\right]/h$$

The neutron magnetic moment $\mu = -1.91\ \mu_N$

$B_0 \simeq 0.01$ gauss

$\nu_n(0) \simeq 30$ Hz

Hence

$$\nu_n(\uparrow\uparrow) - \nu_n(\uparrow\downarrow) = -4\mathcal{E}d_n/h$$

Assuming that B_0 is <u>unchanged</u> when $\mathcal{E}$ is reversed.

PARTICLES DISCUSSED

(Providing good measurements of EDMs)

neutron		dn
~~electron~~ — not directly.		~~de~~
Tl	paramagnetic atom $6p_{1/2} \rightarrow$	(de)
YbF	paramagnetic $^2\Sigma$ molecule $\rightarrow$	(de)
^{199}Hg	diamagnetic atom $^1S_0 \rightarrow$	(d nucleus)
muon		$d\mu$
tau		$d\tau$

The most recent and precise results for particle EDMs

Species examined	Species EDM	Derived EDM	Gain
Neutron	$< 1 \times 10^{-25}$ e cm [1,2]	d(neutron) $< 1 \times 10^{-25}$ e cm	1
Thallium atom	$< 2 \times 10^{-24}$ e cm [3]	d(electron) $< 4 \times 10^{-27}$ e cm	500
YbF molecule	$< 4 \times 10^{-19}$ e cm [4]	d(electron) $< 4 \times 10^{-25}$ e cm	10^5
^{199}Hg atom	$< 9 \times 10^{-28}$ e cm [5]	d(nucleus) $< 1 \times 10^{-24}$ e cm	10^{-3}

[1] K F Smith, N Crampin, J M Pendlebury et al., *Phys. Lett. B* **234**, 191 (1990).

[2] I S Altarev, Yu V Borisov, N V Borikova et al., *Phys. Lett. B* 276, 242 (1992).

[3] E D Commins, B S Ross, D DeMille and B C Regan, *Phys. Rev. A* **50,** 2960 (1994).

[4] B E Sauer, S K Peck, G Redgrave and E A Hinds, *ICAP 15,* Amsterdam (1996).

[5] J P Jacobs, W M Klipstein, S K Lamoreaux et al., Phys. Rev. **52**, 3521 (1995).

Eq. 1

THE ^{199}Hg DIAMAGNETIC ATOM EXPTS

measure d(nucleus)

$\mathbf{J}_{\text{electrons}} = 0$ $\quad$ $\mathbf{J}_{\text{nucleus}} = 1/2$ (one odd neutron)

$$d_{atom} = 1.4 \times 10^{-2}\, d_{electron} + 10^{-3}\, d_{nucleus}$$

$d_{electron}$ term $< 6 \times 10^{-29}$ e cm

since $d_{electron} < 4 \times 10^{-27}$ e cm from the Tl expt [1]

Logic: a d_{atom} close to the experimental limit of 1×10^{-27} e cm [2]

would have to come from the $d_{nucleus}$ term requiring

$$d_{nucleus} \lesssim 1 \times 10^{-24} \text{ e cm}$$

c.f. $d_{neutron} < 1.10^{-25}$ e cm

How can we relate this to $d_{neutron}$? The ^{199}Hg nuclear EDM can be larger than that of the odd neutron it contains. There are amplification effects via T-violating parts of the internucleon forces. The gain can roughly lie between 3 and 300 depending on the mechanism concerned.

- QCD θ term gain = 3 bare neutron wins by about factor of 3
- SUSY gain = 10 comparable with bare neutron
- multi Higgs gain = 50 5 times better than bare neutron
- LR Symmetric gain = 200 20 times better

[1] E D Commins, B S Ross, D DeMille and B C Regan, *Phys. Rev. A* **50**, 2960 (1994).

[2] J P Jacobs, W M Klipstein, S K Lamoreaux et al., *Phys. Rev.* **52**, 3521 (1995).

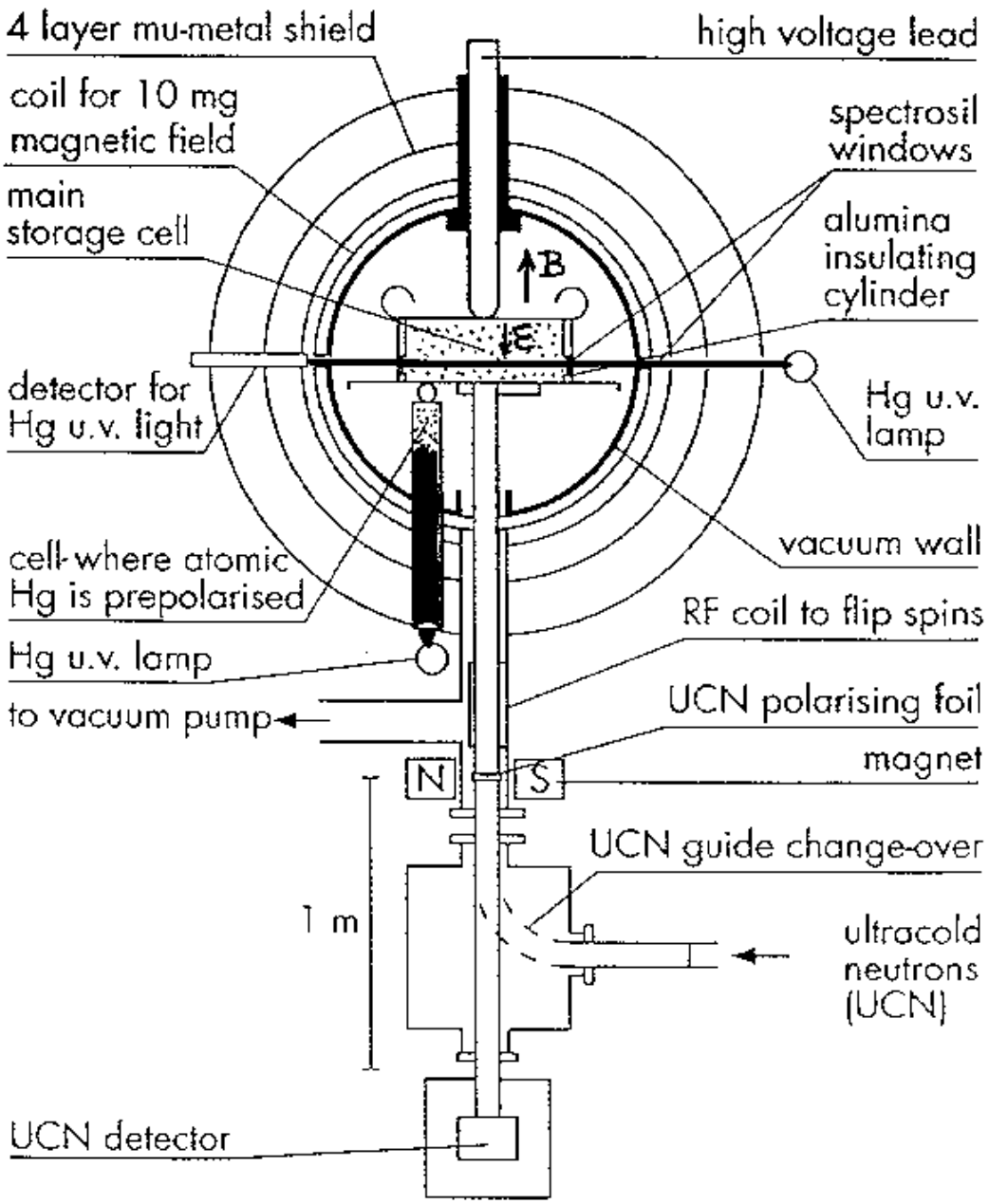
NEUTRON ELECTRIC DIPOLE MOMENT MEASUREMENTS BY THE GROUP AT SUSSEX

(1) SUSSEX at Aldermaston	1970	$d_n < 5.10^{-22}$ e cm
(2) ORNL-SUSSEX-HARVARD at ILL, Grenoble	1977	$d_n < 3.10^{-24}$ e cm
(3) SUSSEX-RAL-HARVARD at ILL, Grenoble	1984	$d_n < 7.10^{-25}$ e cm
(4) SUSSEX-RAL-WASHINGTON at ILL, Grenoble	1990	$d_n < 1.2\ 10^{-25}$ e cm
(5)	1999	$d_n < 2.4\ 10^{-26}$ e cm

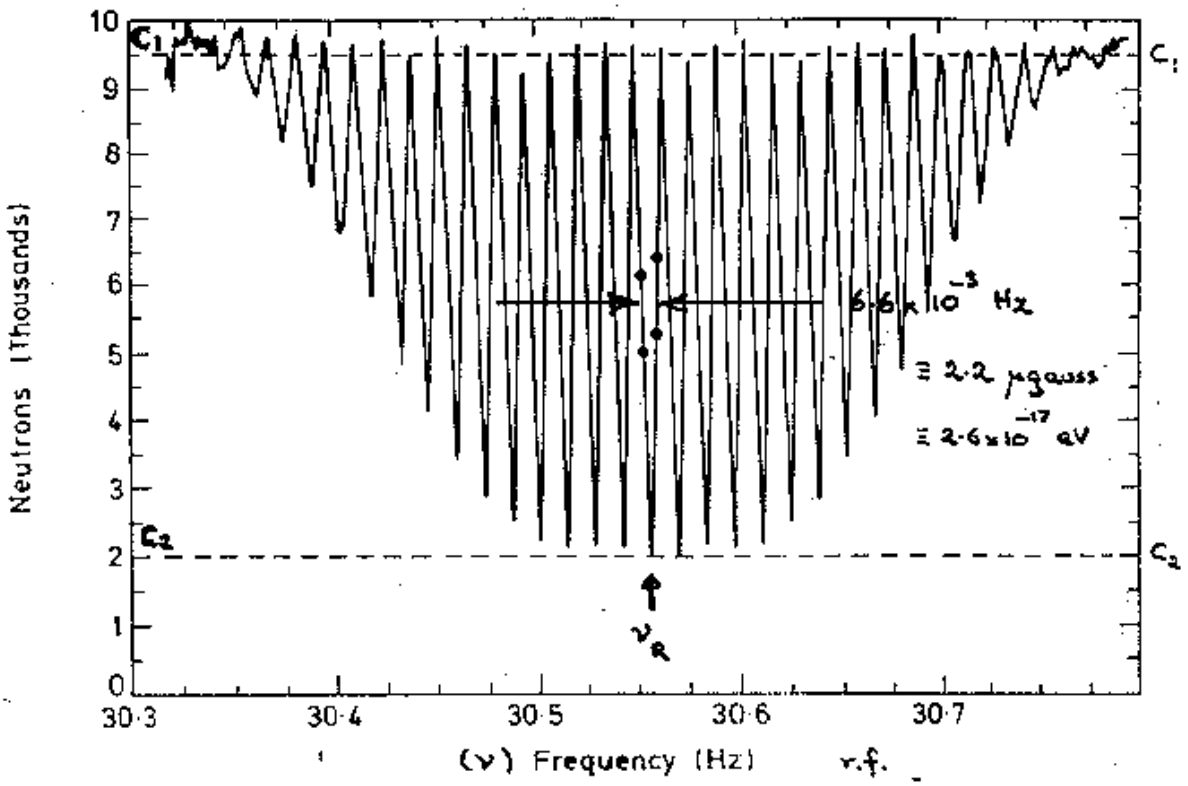
SUSSEX-RAL-WASHINGTON-PETERSBURG NPI
at ILL, Grenoble
expt. with cohabiting ^{199}Hg magnetometer

THE NEW NEUTRON EDM EXPERIMENT

Data to be taken at ILL 1996-1999



Double Pulse (Ramsey) Resonance Curve



If the number of particles finishing in the other M_J state can be measured separately, it is a useful extra data and improves the statistics. A working point for the EDM measurement is chosen by setting the oscillator frequency for one of the steepest points at the half height close to the centre of the resonance pattern. A given period of running yields N counts where $N = N_1 + N_2$ and the latter refer to the two M_J states concerned. The running time is shared equally between the two directions of **E** with the counts being binned separately to give $N_{1\rightleftarrows}$ $N_{1=}$ $N_{2=}$ $N_{2\rightleftarrows}$. The dipole moment can be obtained using

$$d_a = \frac{(N_{1\rightleftarrows} - N_{1=} - N_{2\rightleftarrows} + N_{2=})J\hbar}{\alpha ETN} \tag{4}$$

where $\alpha = (N_{\max} - N_{\min})/(N_{\max} + N_{\min})$ is the 'visibility' of the resonance pattern in the vicinity of the working point. Alpha includes all factors which make the polarisation of the atoms less than complete at the end of the free precession including failure to polarise completely in the first place, subsequent spin relaxation, and any inefficiency in the final polarisation analysis. In the neutron experiments $\alpha = 0.6$ would be a typical value. In deriving (4) α was taken to be the same for both final states.

3.1 Statistics

From the previous equation it follows that the minimum standard deviation for the d_a measurement coming from the counting statistics alone is given by

$$\sigma_{d_a} = \frac{J\hbar}{\alpha ET\sqrt{N}} \tag{5}$$

The full range of experiments covers a wide variety of values for these parameters. The highest Es are generated microscopically, for example, those found inside molecules which may be used for d_e measurements $\sim 3 \times 10^7$ kV/cm and in the atomic cores within single polar crystals which might be used with neutron beam measurements $\sim 10^6$ kV/cm. It happens that experiments using these two beam systems involve rather short times T of $\sim 10^{-3}$ s and only moderate particle counting rates N /s of $\sim 10^3$. At the other extreme, the lowest E values ~ 10 kV/cm are in trap experiments where the limitation comes from the bad behaviour of the trap insulating side walls which are parallel to, and immersed in, the field. In compensation, the times T are long in traps, ~ 100 s and the counting rates are moderate to large, ranging from 10^2 /s to 10^{10} /s.

3.2 Magnetometers

If there is a small change in B when **E** is reversed, even as small as 10^{-10} gauss, (3) has to be modified to become

$$(\nu_{=} - \nu_{\rightleftarrows})Jh - \mu_a(B_{\rightleftarrows} - B_{=}) = 2d_aE. \tag{6}$$

It is evident that this extra term must be measured and corrected for lest it create a systematic error. There are two approaches. Firstly, a different atomic species may be used as a magnetometer to measure $B_{\rightleftarrows}$ and $B_{=}$; for example, Cs and Rb magnetometers have

Recent data from the Neutron EDM Experiment running at ILL

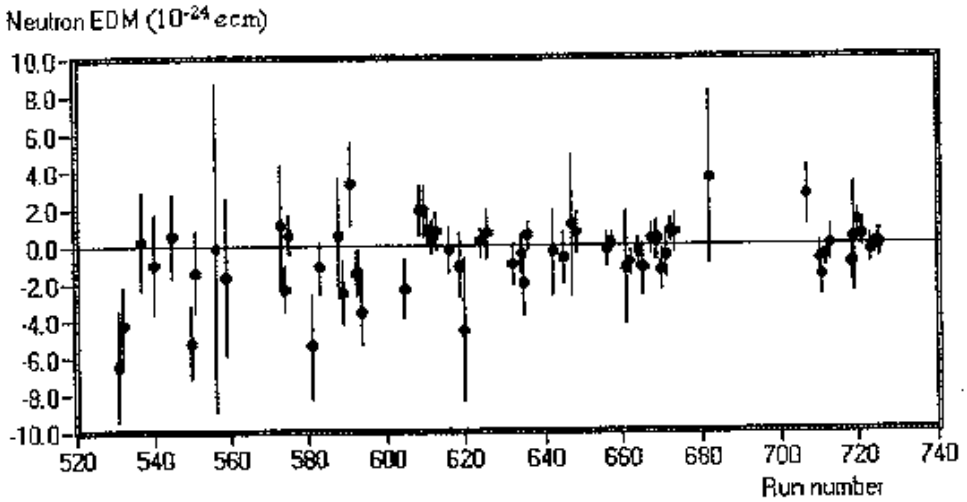
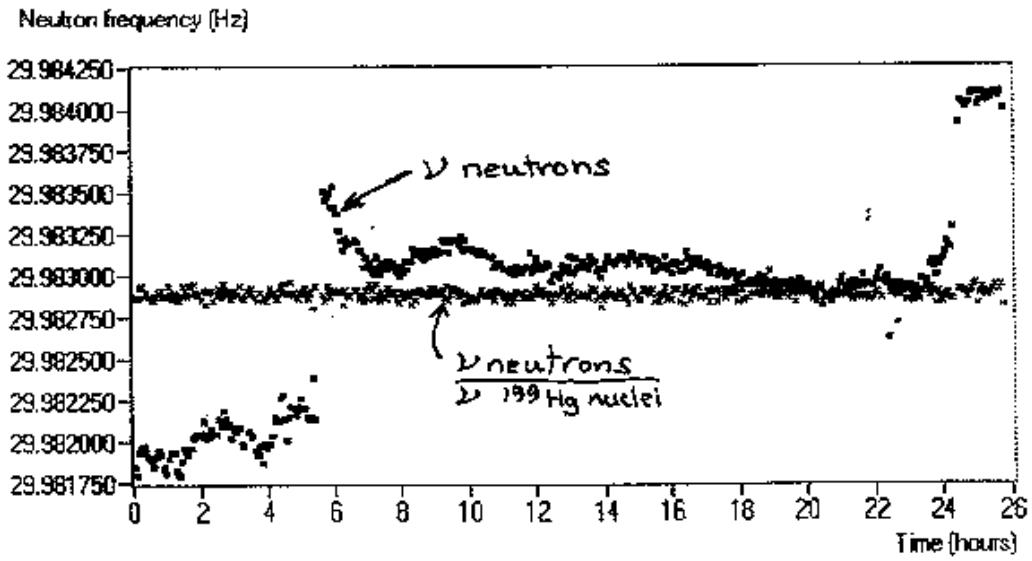
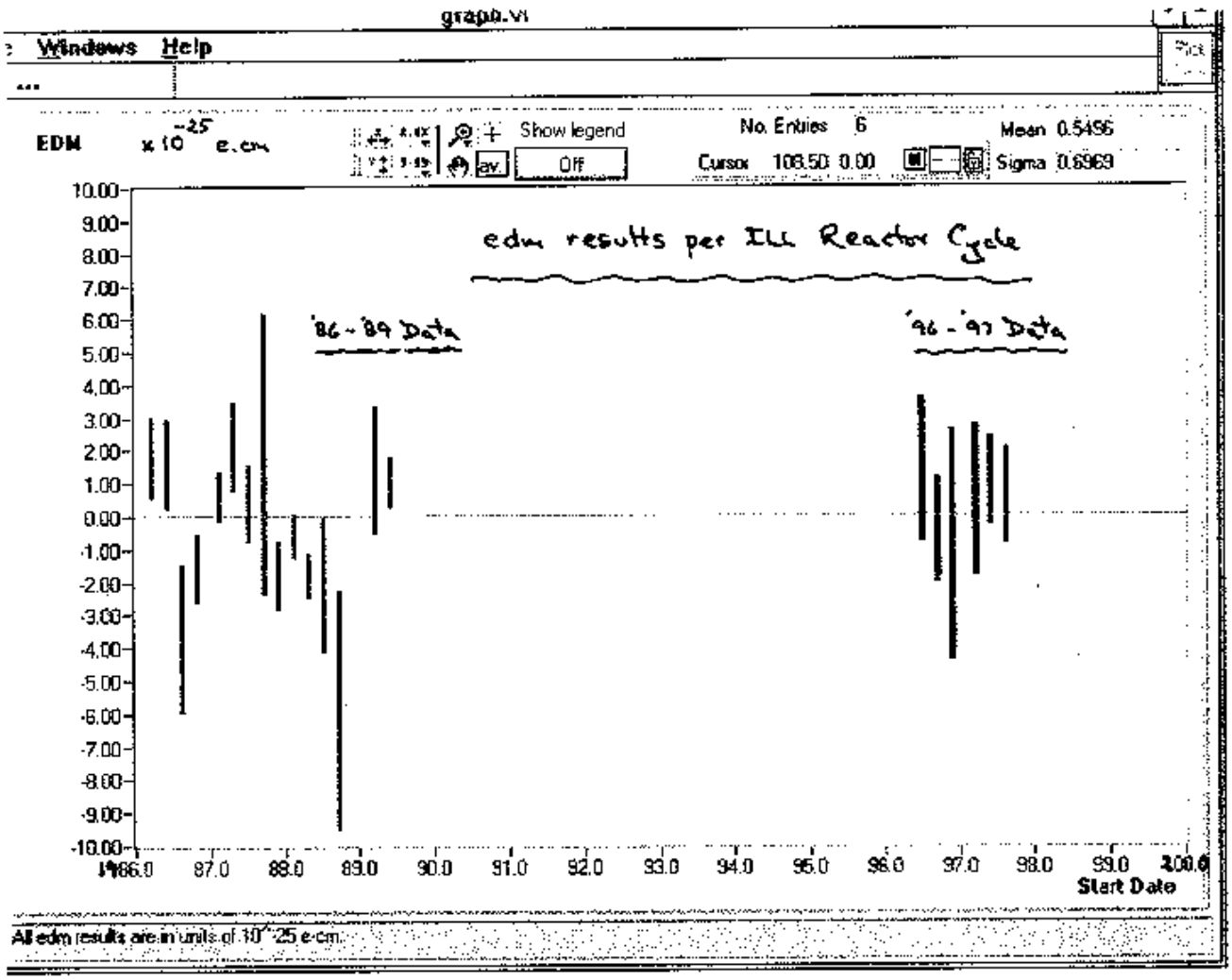


Figure 1. Showing preliminary results from data obtained during four ILL reactor cycles





$edm = -(0.3 \pm 0.5)\,10^{-25}$ e.cm

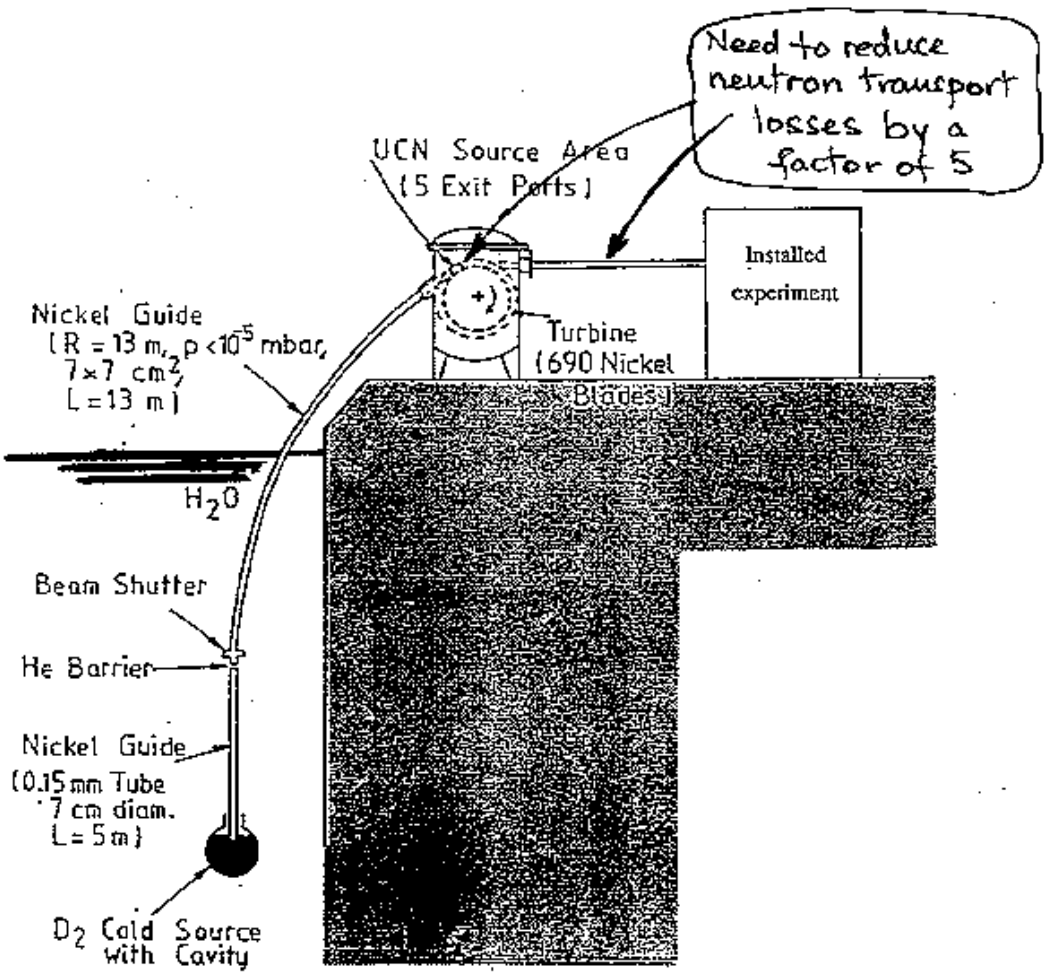
w/ $\chi^2/dof = 2.2$

$edm = (0.55 \pm 0.70)\,10^{-25}$ e.cm

w/ $\chi^2/dof = 0.2$

ULTRACOLD NEUTRON FACILITY (UCN)

PF2



At the ~~experiment~~ turbine the
UCN Number density for v < 6 m/s

50 /cm3 or

50000 /litre

GOALS OF FUTURE NEUTRON EDM PROJECTS
LOW TEMPERATURE (0.5 K) EXPERIMENTS
1997 - 2015

Methods

(1) to generate the stored neutrons (10^{-7} eV) by scattering cold beam neutrons (10^{-3} eV) in liq ^{4}He at 0.5 K
(2) to fill the other apparatus regions occupied by stored neutrons with liq ^{4}He at 0.5 K
(3) to use a superconducting inner magnetic shield
(4) to use squid magnetometer

Estimated performance

Current Phase	Next Phase	Next but one phase
4 kV/cm	24 kV/cm	24kV/cm
200 s	200 s	200 s
10^7 /day	4×10^7 /day (Guide n beam)	2.5×10^9/day (Broader n beam) dedicated

$d_n < 2.5\times10^{-26}$ e cm	$d_n < 2\times10^{-27}$ e cm	$d_n < 2.5\times10^{-28}$ e cm

CONCLUSIONS

Theory

- Particle EDMs are continue to be useful for constraining models of CP violation beyond the MSM.

- Currently, the electron, the neutron and nuclei are all of importance. Between them they offer some discrimination, E.g. the electron EDM ignores the QCD theta mechanism.

- The cases of the neutron and nuclei bring in some QCD structure caculations.

- Minimum SUSY can just live with the existing results, but is but is pressed by all the EDMs, electron, neutron and nuclear.

Experiment

- d(electron) can be improved a factor of 10 using the YbF paramagnetic molecule (3 years).
  In the longer term this method may reach a factor of 100.

- d(neutron) can be improved by a factor of 3 using the new machine at ILL (3 years).
  In the longer term (10 years) a new kind of apparatus with storage of neutrons in liquid He could reach 100.

- d(nucleus) can be improved via the ^{199}Hg atom perhaps by another factor of 10 in 3-5 years.