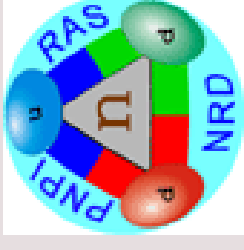*Petersburg Nuclear Physics Institute*

Neutron Research Division

Measuring EDM of the electron – ongoing and planned experiments

Mikhail Kozlov

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- Electric dipole moment of the electron (eEDM) in SUSY

- Atomic enhancement of eEDM

- Additional enhancement of eEDM in diatomic radicals

- Spectroscopic beam experiments

- Solid state magnetization in electric field

- List of ongoing & planned experiments

Current limit on eEDM

Atomic beam experiment on Tl by Commins' group in Berkeley gave the following upper limit for EDM of Tl atom [Regan et al (2002)]:

$$|d_{\mathsf{Tl}}| < 9 \times 10^{-25} \; e \; \text{cm}.$$

Atomic theory allows to link d_{Tl} with eEDM d_e:

$$d_{\mathsf{Tl}} = -590 \times d_e.$$

That leads to the upper bound to d_e:

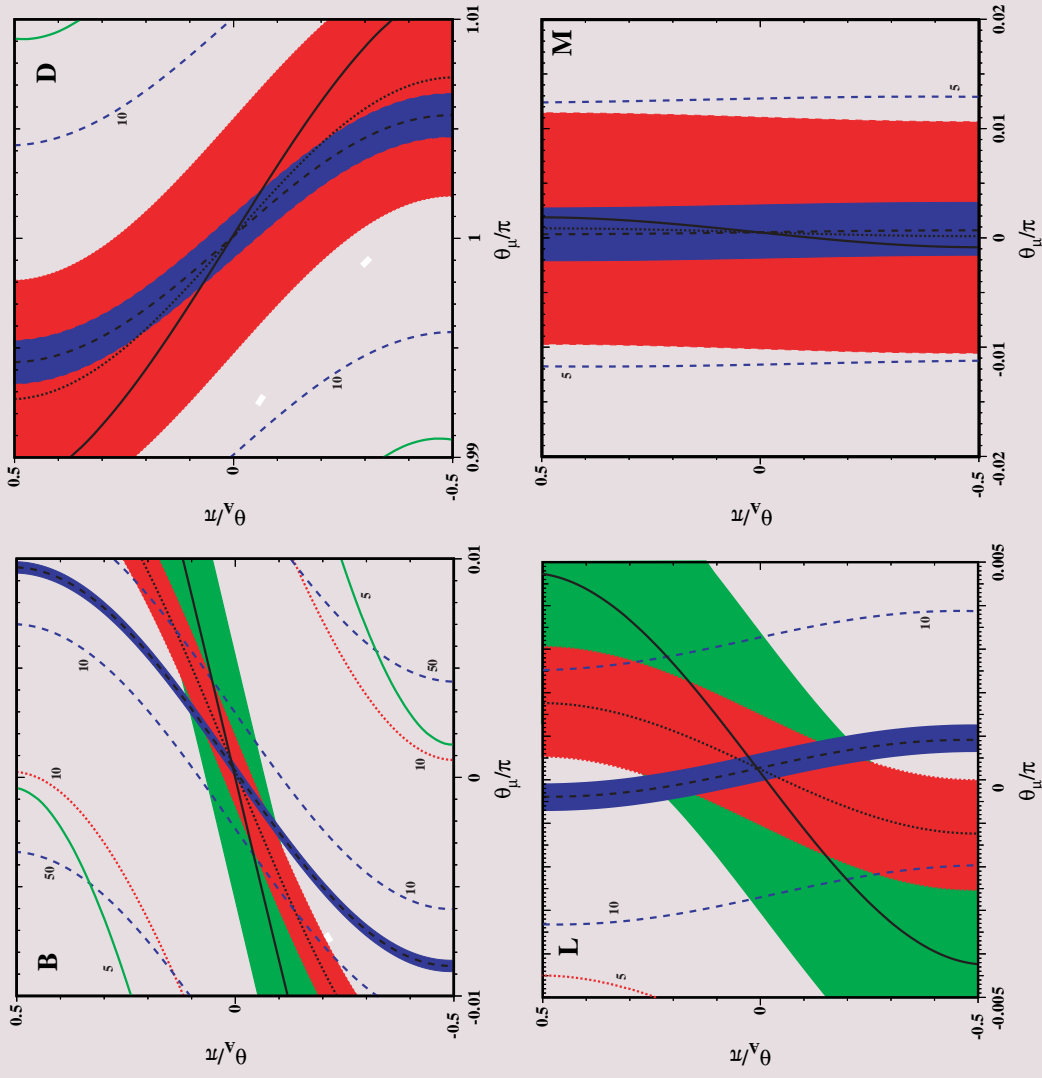$$|d_e| < 1.6 \times 10^{-27} \; e \; \text{cm}.$$

Rewrite this in the length units of the classical electron radius r_e:

$$\boxed{|d_e/(e \; r_e)| < 5.7 \times 10^{-15}.}$$

Experimental limits on
the CP-odd phases
in the minimal SUSY
model from EDM ex-
periments on Tl, Hg,
and n.

Four choices of other
parameters of the
model are selected
to demonstrate dif-
ferent possibilities.

[Olive,Pospelov,Ritz,
Santoso, e-print:
physics/0509106]

Atomic enhancement of the eEDM

Non-relativistic consideration of the electron in the stationary state immediately leads to the zero energy shift:

$$\delta\varepsilon = -\vec{d}_e \cdot \langle\vec{E}\rangle; \quad m\vec{a} = -e\vec{E}; \quad \langle\vec{a}\rangle = 0; \quad \Rightarrow \quad \langle\vec{E}\rangle = 0.$$

However, in the electron rest frame there is nonzero magnetic field and the force $\vec{F} \neq -e\vec{E}$. Therefore, generally $\langle\vec{E}\rangle \neq 0$.

Relativistic Hamiltonian for the Dirac electron has the form:

$$H_d = -d_e \begin{pmatrix} \vec{\sigma} & 0 \\ 0 & -\vec{\sigma} \end{pmatrix} \cdot \vec{\nabla}\phi \blacktriangle\blacktriangle\blacktriangle H_d = 2d_e \begin{pmatrix} 0 & 0 \\ 0 & \vec{\sigma} \end{pmatrix} \cdot \vec{\nabla}\phi,$$

where ϕ is atomic potential. In the external electric field $\vec{E}$ the energy correction will be:

$$\delta\varepsilon = 2\frac{\langle 0|H_d|n\rangle\langle n|e\vec{r}\cdot\vec{E}|0\rangle}{\varepsilon_0 - \varepsilon_n}.$$

Estimate of atomic energy shift due to eEDM
[Sandars 1965, Flambaum 1976]

In atomic units $(\varepsilon_0 - \varepsilon_n) \sim \langle n|r|0\rangle \sim 1$ and

$$\delta\varepsilon \sim \langle H_d\rangle E = 2d_e E \left\langle \left(\begin{pmatrix} 0 & 0 \\ 0 & \vec{\sigma} \end{pmatrix}\right) \cdot \vec{\nabla}\phi \right\rangle .$$

At large distances $\phi \sim 1$, but for $r \sim \frac{1}{Z}$, $\phi \sim \frac{Z}{r}$ and $\nabla\phi \sim \frac{Z}{r^2} \sim Z^3$. Also, at large distances the small components of the Dirac orbitals $\sim \alpha$, while at short distances they are $\sim \alpha Z \times \psi(0) \sim \alpha Z^{3/2}$. As a result, the above matrix element is given by the integral over the volume $V \sim Z^{-3}$:

$$\delta\varepsilon \equiv d_{\text{at}} E \sim d_e E (\alpha Z)^2 \psi^2(0) \left(\nabla\phi|_{r\sim 1/Z} V\right) \sim \alpha^2 Z^3 d_e E.$$

We see that $d_{\text{at}} \equiv k_{\text{at}} d_e \sim \alpha^2 Z^3 d_e$ and atomic enhancement factor

$$\boxed{k_{\text{at}} \sim \alpha^2 Z^3 .}$$

Calculations of atomic enhancement factors

The estimate $k_{at} \sim \alpha^2 Z^3$ obtained by Flambaum showed that heavy atoms could work as amplifiers of eEDM. That was later confirmed by accurate atomic calculations. For example, for Cs (Z=55), $k_{Cs} \approx 120$ and for Tl (Z=81) $k_{Tl} \approx -590$.

Atomic enhancement factors appear to be very sensitive to electron correlations. In particular, the Dirac-Fock calculation for Tl gives $k_{Tl} = -1910$.

Core-valence correlations usually increase the answer by $10 - 30\%$, while valence-valence correlations can work both ways.

Note that k_{at} depends on $|\psi_{val}(0)|^2$ and, therefore, becomes small when the angular momentum of the valence electron $j > \frac{1}{2}$. For this case correlations can even change the sign and the order of magnitude of the effect.

Summary for atoms

- Atomic EDM scales as $10\alpha^2 Z^3 \times d_e$ when valence electron has $j = \frac{1}{2}$ and is much smaller otherwise.

- The sign of d_{at} depends on the valence configuration.

- Atomic enhancement factor k_{at} is very sensitive to electron correlations, in particular for the case of $j > \frac{1}{2}$.

- Modern atomic theory allows reliable calculations of k_{at} for most heavy atoms of interest.

eEDM in diatomic molecules

- Internal electric field in the polar molecule $E_{\text{mol}} \sim \frac{e}{R_o^2} \sim 10^9\,\text{V/cm}$, which is $4-5$ orders of magnitude larger than typical laboratory field in EDM experiment. This field is directed along the molecular axis and is averaged by rotation of the molecule.

- In the external electric field E_{lab} molecular axis is polarized in the direction of the field. For $\Sigma_{1/2}$-molecule in the rotational level J the complete polarization requires the field $D_{\text{mol}}E_{\text{lab}} \approx 2BJ$. For molecules with Ω-doubling a much smaller field may be sufficient.

- Typical molecular enhancement factor $\boxed{k_{\text{mol}} \sim k_{\text{at}} \times \frac{E_{\text{mol}}}{E_{\text{lab}}} \sim 10^4 k_{\text{at}}.}$

Molecules with large enhancement

- The molecule must have non-zero electronic angular momentum $\Rightarrow$ unpaired electron(s). Thus, it can be either a molecule in excited state [PbO in $a(1)$ state], or a radical [PbF, YbF, etc.].

- Unpaired electron(s) must be in orbitals with $\omega = \frac{1}{2}$. [YbF and PbF have $\sigma_{1/2}$ and $\pi_{1/2}$ electron;PbO has configuration $\pi_{3/2}\pi^*_{-1/2}$.]

- The molecule must have heavy atom and non-zero dipole moment. Unpaired electron must be centered on the heavy atom.

$\Rightarrow$ HgF, HgH, PbF, and YbF are likely to have large enhancement in the ground state. Metastable $a(1)$ state of PbO is also likely to have large enhancement. On the contrary, CsO and IO are not good candidates: for CsO the unpaired electron is on oxygen and IO has ground state $\Pi_{3/2}$.

Molecular calculations

Diatomics in the ground state $\Sigma_{1/2}$ can be calculated with semiempirical and *ab initio* methods. Results of different calculations typically agree within $10 - 20\%$. [BaF, YbF, HgF, HgH]

Semiempirical calculations for $\Pi_{1/2}$ are less reliable, but *ab initio* calculations should be of a similar quality as for $\Sigma_{1/2}$ molecules. [PbF]

State $a(1)$ of PbO is tough for both semiempirical and *ab initio* methods. Results differ by a factor of 2. There is strong configuration mixing.

Molecular ions HBr^+ and HI^+ were calculated with atomic perturbation theory and with molecular codes. Last molecular calculation is closer to atomic estimate, but still 2 times smaller. Enhancement is likely to be 2 orders of magnitude smaller than for HgF.
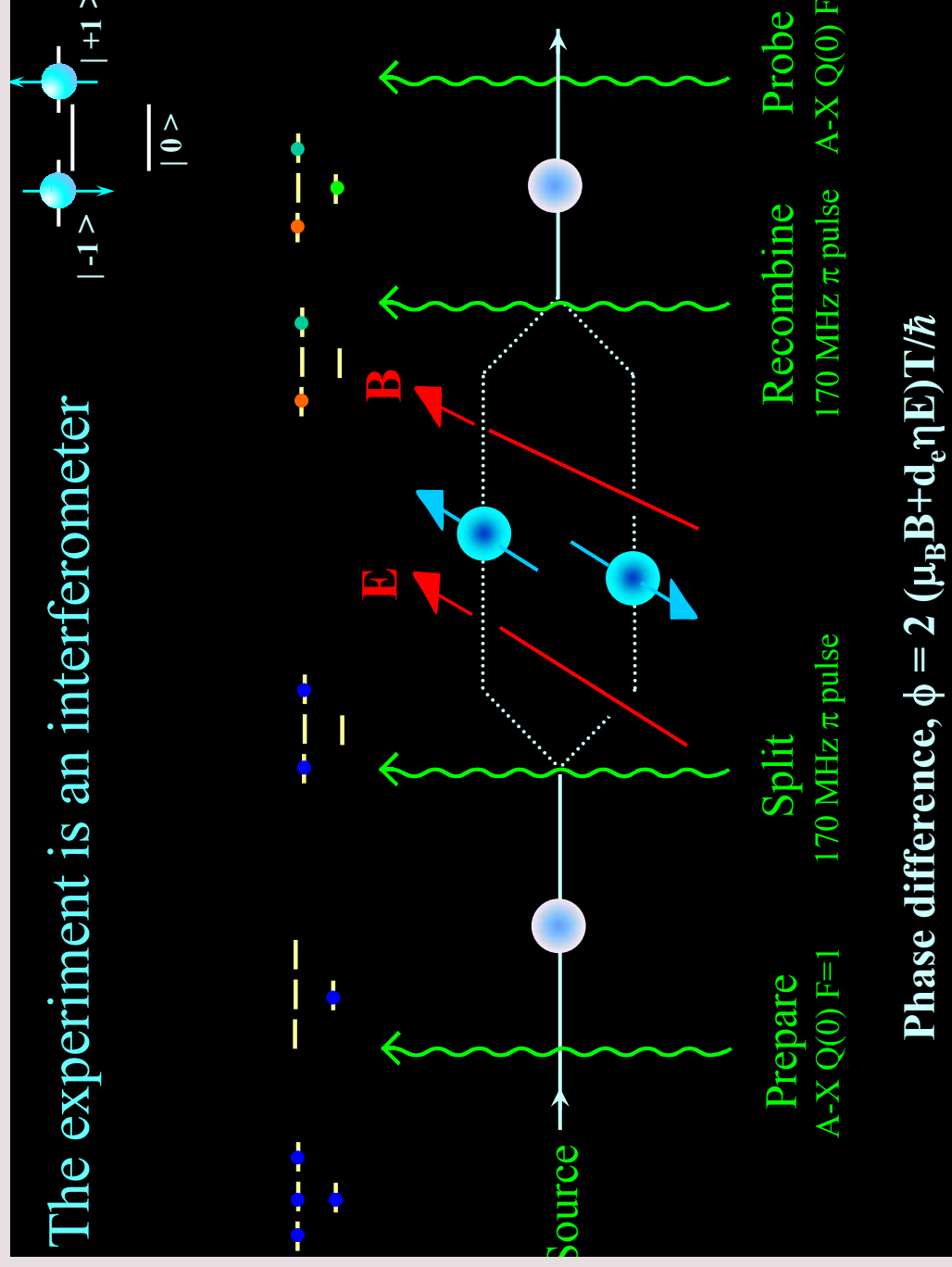
Summary for diatomic molecules

Theory

Ω	Polarization field	E_{eff} (au)	Reliability of calculations	Examples
$\frac{1}{2}$	few kV/cm	$\alpha^2 Z^3$	high	HgH, YbF, PbF
1	few V/cm	$\alpha^2 Z^3$	normal	PbO*
$\frac{3}{2}$	$\ll$ V/cm	$0.1\alpha^2 Z^3$	low	HBr$^+$, HI$^+$

Experiment

At present experiments are going on YbF in London and on PbO in Yale. Experiment on PbF is planned in Oklahoma. Experiments with trapped molecular ions are planned in Boulder.

Molecular beam experiment [Ben Sauer, UCN-2005]

The experiment is an interferometer

$|{-1}\rangle$ $|0\rangle$ $|{+1}\rangle$

B
E

Source

Prepare
A-X Q(0) F=1

Split
170 MHz π pulse

Recombine
170 MHz π pulse

Probe
A-X Q(0) F

Phase difference, $\phi = 2\,(\mu_B B + d_e \eta E)T/\hbar$

Solid state

In 1968 Shapiro suggested to look for magnetization of a paramagnetic substance with unpaired electrons in the external electric field. Enhancement factor here is roughly k_{at}/ε.
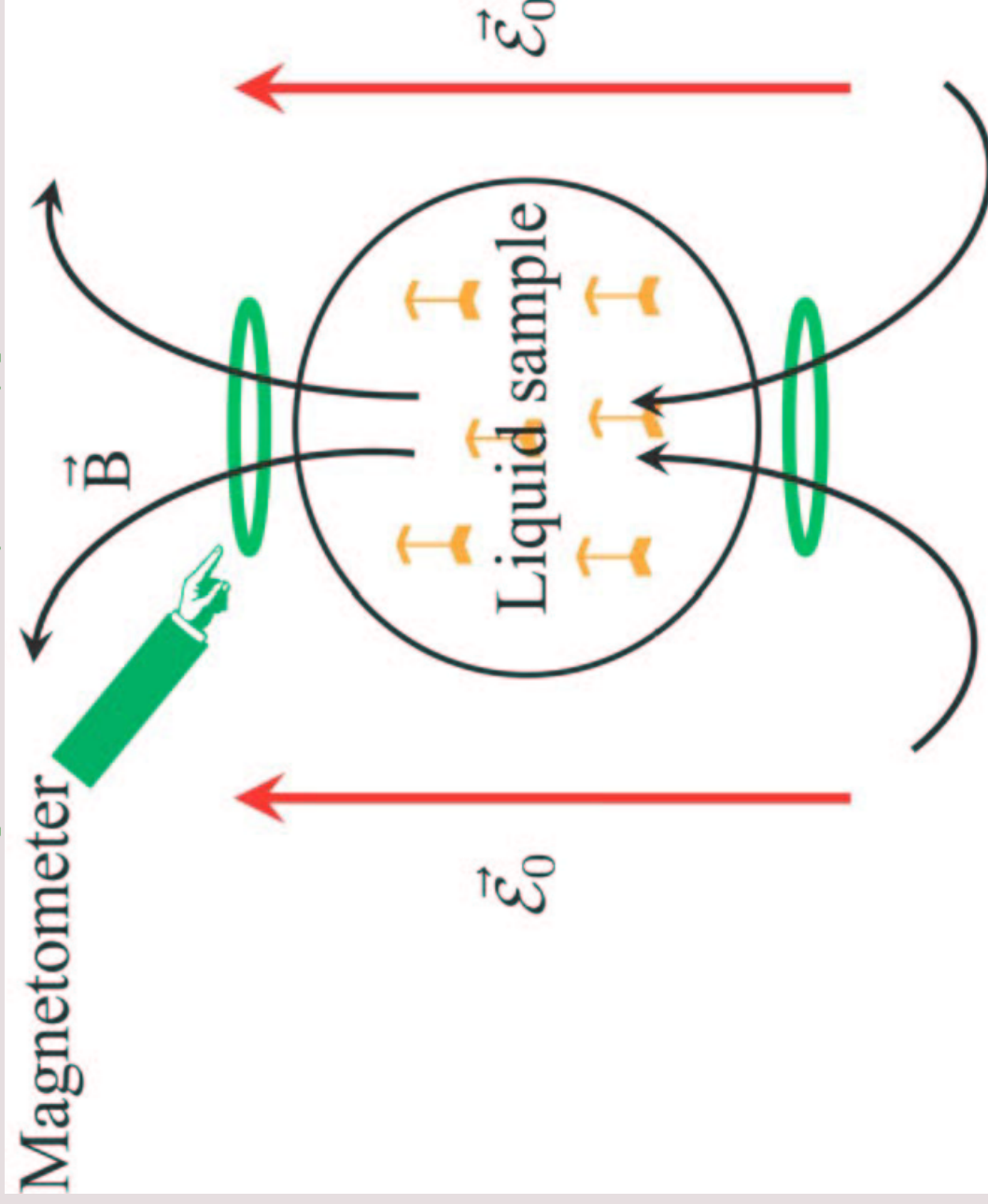
Magnetic flux is proportional to the spin density and the surface area. Thus, it is advantageous to do experiment with macroscopic solid sample. Such experiment was done in 1978 by Vasil'ev & Kolicheva.

In 2001 Lamoreaux showed that advances in magnetometry and new materials, such as gadolinium garnets, allow to raise current sensitivity to eEDM by several orders of magnitude.

Similar experiment can be done with diatomic radicals in a noble gas matrix. Here we can have 5 orders of magnitude gain in the enhancement factor. The number of spins will be $4 \div 6$ orders of magnitude smaller, $\Rightarrow$ the net gain $10^2 \div 10^3$ in S/N [Kozlov & Derevianko, 2006].

In 2004 Baryshevsky pointed out that similar experiments can be done with diamagnetic samples. Effect is weaker there, but magnetic noise is also smaller. Again, one can enhance the effect by using polar molecules in a liquid [Derevianko & Kozlov, 2005].

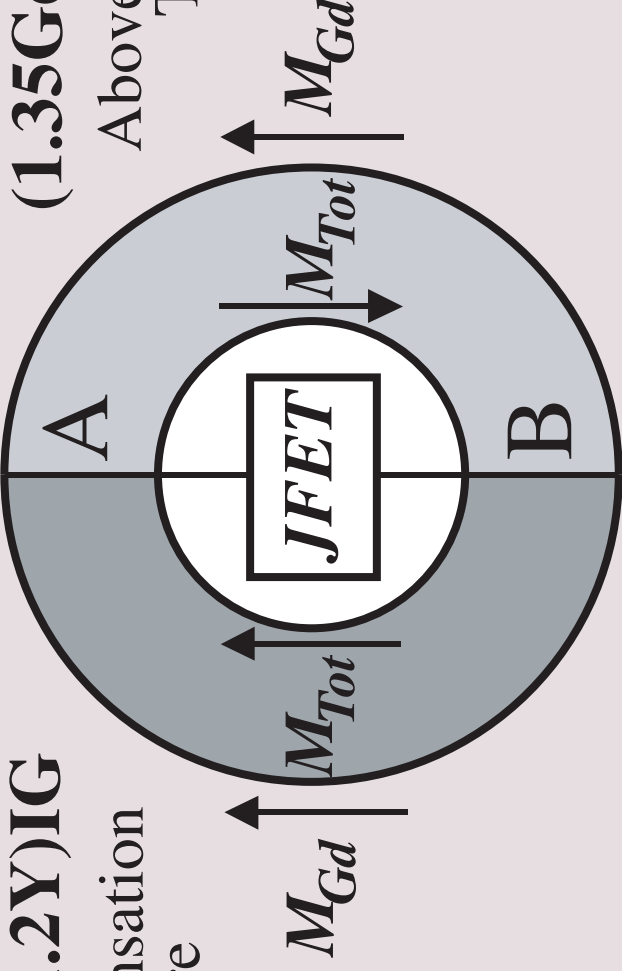Magnetization in the external electric field [Shapiro (1968)]

eEDM experiment with Gadolinium-Iron Garnet (GdIG)
[Heidenreich *et al.* PRL, **95**, 253004 (2005)]

(1.35Gd, 1.65Y)IG
Above Compensation Temperature

M_{Gd}

M_{Tot}

A

B

JFET

M_{Tot}

M_{Gd}

(1.8Gd, 1.2Y)IG
Below Compensation Temperature

List of ongoing & planned experiments

Group	Object			Method	Status	Result (e cm)
IC London	YbF	d_e	beam	spectroscopy	data collection	10^{-27}/day
Yale	PbO	d_e	cell	spectroscopy	testing	—
Gatchina	TlF	S	beam	spectroscopy	testing	—
Oklahoma	PbF	d_e	trap	spectroscopy	design	—
JILA	HfH$^+$	d_e	trap	spectroscopy	design	—
Amherst	Gd^{3+}	d_e	GdIG	voltage	testing	10^{-24}
Los Alamos	Gd^{3+}	d_e	GdGG	magnetometery	testing	10^{-23}
Princeton	^{129}Xe	S	liquid	magnetometery	testing	—
	HgH	d_e	matrix	magnetometery	proposal	—