# Electric dipole moment of electron in solids: prospectives and theoretical problems.

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**Electric Dipole Moment (EDM) of electron $d_e$**

Present upper limit $d_e < 1.6\ 10^{-27}$ e cm comes from experiment with atomic Tl beam.
Regan, Commins, Schmidt, DeMille (2002).

Experiments with solids were suggested by F. L. Shapiro in 1968.

Following the suggestion measurements with Nickel Zinc ferrite were performed by Vasil’ev and Kolycheva in 1978.
Results were not impressive.

## Recent renewal of interest to solid state measurements

Proposals:

Lamoreaux 2002, Gadolinium Gallium Garnet (GGG)

Hunter 2002, Gadolinium Iron Garnet (GIG), ferrimagnetic state

Lamoreaux 2007, Gadolinium Iron Garnet, superparamagnetism

Experiment with ferrimagnetic GIG, 2005, Heidenrich et al,
$d_e < 5\ 10^{-25}$ e cm.

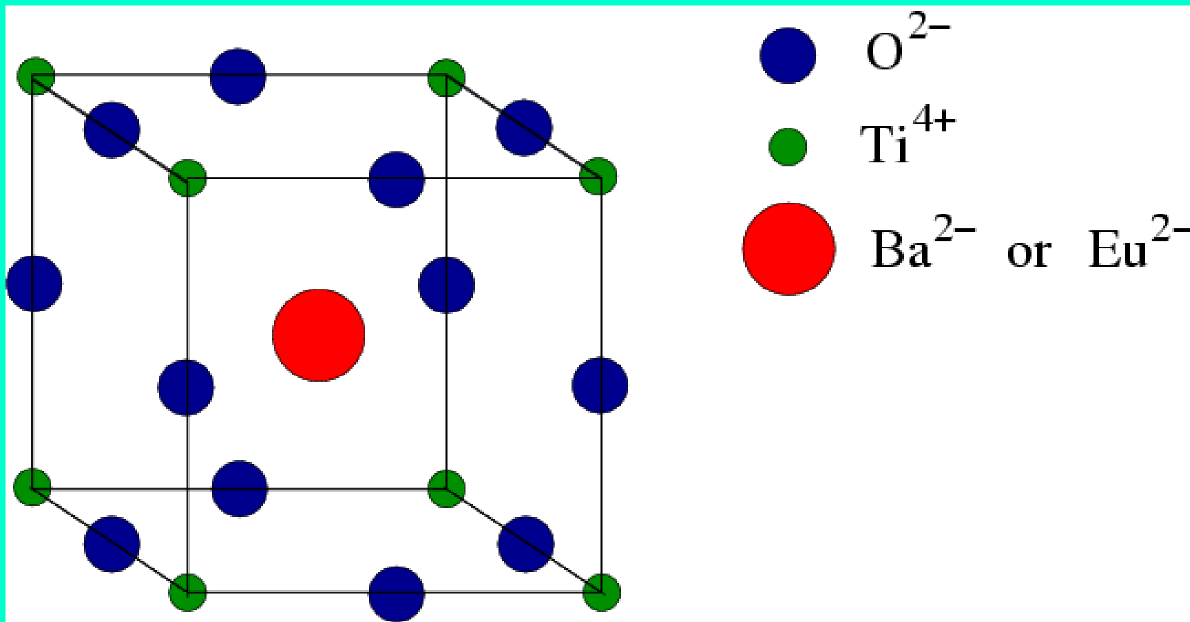
It is clear now that garnets are not suitable

1) GGG: limitation comes from spin freezing at T ~ 1K
2) Ferrimeagnetic GIG: limitation comes from a magnetoelectric effect (multiferroic).
3) Superparamagnetic GIG: limitation comes from magnetic noise.

A. O. Sushkov, S. Eckel, S. K. Lamoreaux, 2008

$Eu_{0.5}Ba_{0.5}TiO_3$:
a material specially designed and synthesized for the electron EDM experiment.

Room temperature crystal structure.

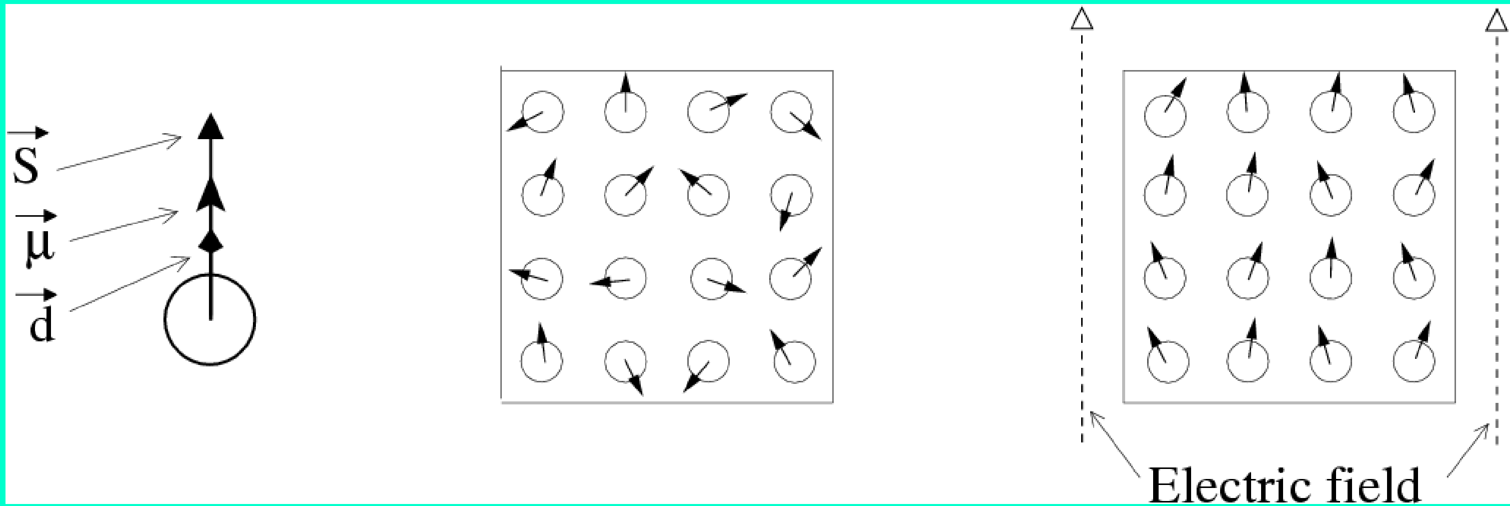


$Eu_{0.5}Ba_{0.5}TiO_3$
is ferroelectric at T < 160K,
and it is ferromagnetic at T < 2K.
So, technically this material is a multifferroic

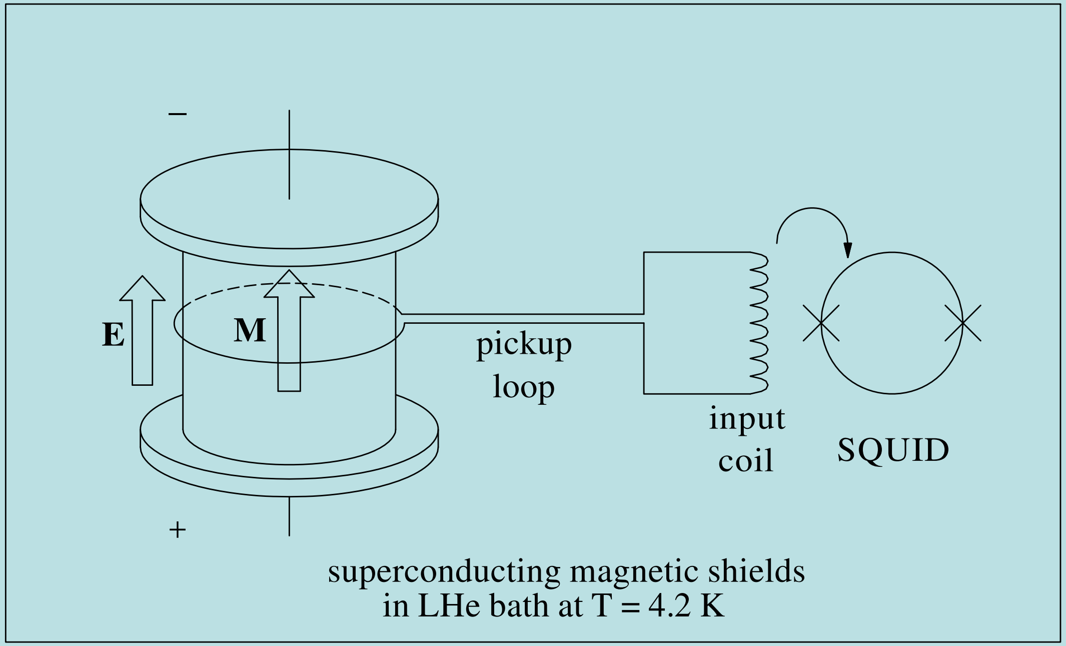
Optimal temperature for the EDM experiment is T ~ 4K.
At this temperature $Eu_{0.5}Ba_{0.5}TiO_3$ is
a ferroelectric paramagnet

Effective internal electric field **$E \sim 10^7$ V/cm**
**$Eu^{2+}$** ion has spin **S=7/2** (electron configuration **$f^7$**)
Density of magnetic ions **$n_{Eu} = 6\ 10^{21} 1/cm^3$**

# Idea of the experiment is pretty simple




Experimental setup



**A very naïve estimate.**
**In the end the estimate is correct**

Energy shift due to EDM:

$$\delta\varepsilon = -d_e E_{eff}$$

Induced magnetization:

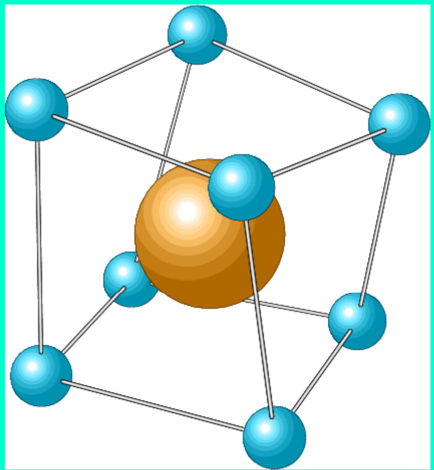
$$\delta\mu \sim n\mu_B \frac{\delta\varepsilon}{T}$$

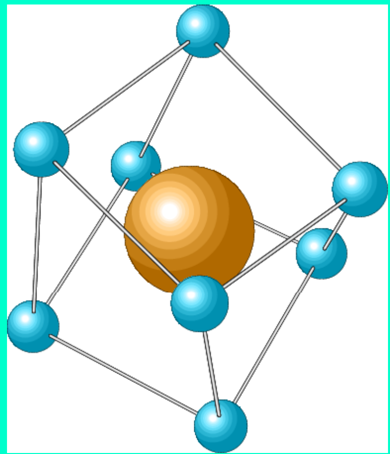
**With $E_{eff} \sim 10^7$V/cm, n~ $10^{22}$1/cm$^3$, T =4K**
**the gain in sensitivity is about 10 compared to the present level**

**Question to theory: how to calculate $E_{eff}$?**

Theoretical estimates of the effect:
Kuenzi, O.P. Sushkov, Dzuba, Cadogan, 2002,
Mukhamedjanov, Dzuba, O. P. Sushkov, 2003.

The estimates have been performed for GGG





$Gd^{3+}$ in the cage of $O^{2-}$ ions

2p-electrons of $O^{2-}$ ions penetrate to Gd nucleus.

The spin-dependant energy shift reads

$$\delta\varepsilon = -A \times 27.2eV \times \left(\frac{d_e}{ea_B}\right) \times \left(\frac{\vec{x}\cdot\vec{S}}{a_B(7/2)}\right)$$

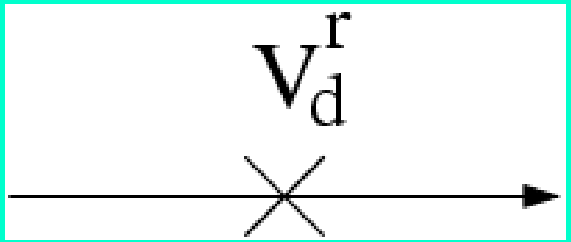
**S** is spin of the Rare Earth ion.
**x** is displacement of the ion from center of the cage

EDM Hamiltonian

$$V_d = -d_e \gamma_0 \vec{\Sigma} \cdot \vec{E} \quad , \qquad \vec{\Sigma} = \gamma_0 \gamma_5 \vec{\gamma}$$

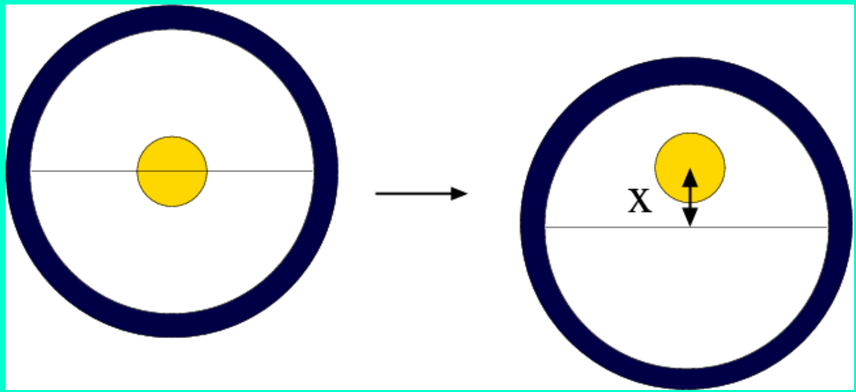
Account for the Schiff theorem

$$V_d \to V_d^r = -d_e (\gamma_0 - 1) \vec{\Sigma} \cdot \vec{E}$$



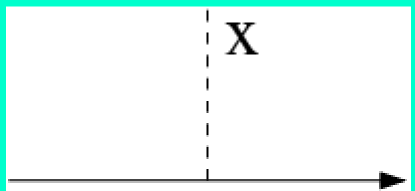

Diagramatic notation for $V_d$

Jelly model: spread oxygen ions of the cage over a spherical shell




Rare Earth ion inside spherical oxygen cage.
**x** is displacement with respect to the cage center.
The displacement is due to external electric filed in a paraelectric.
The displacement is due ferroelectricity in a ferroelectroic

The displacement mixes s- and p-orbitals centered at the Rare Earth ion

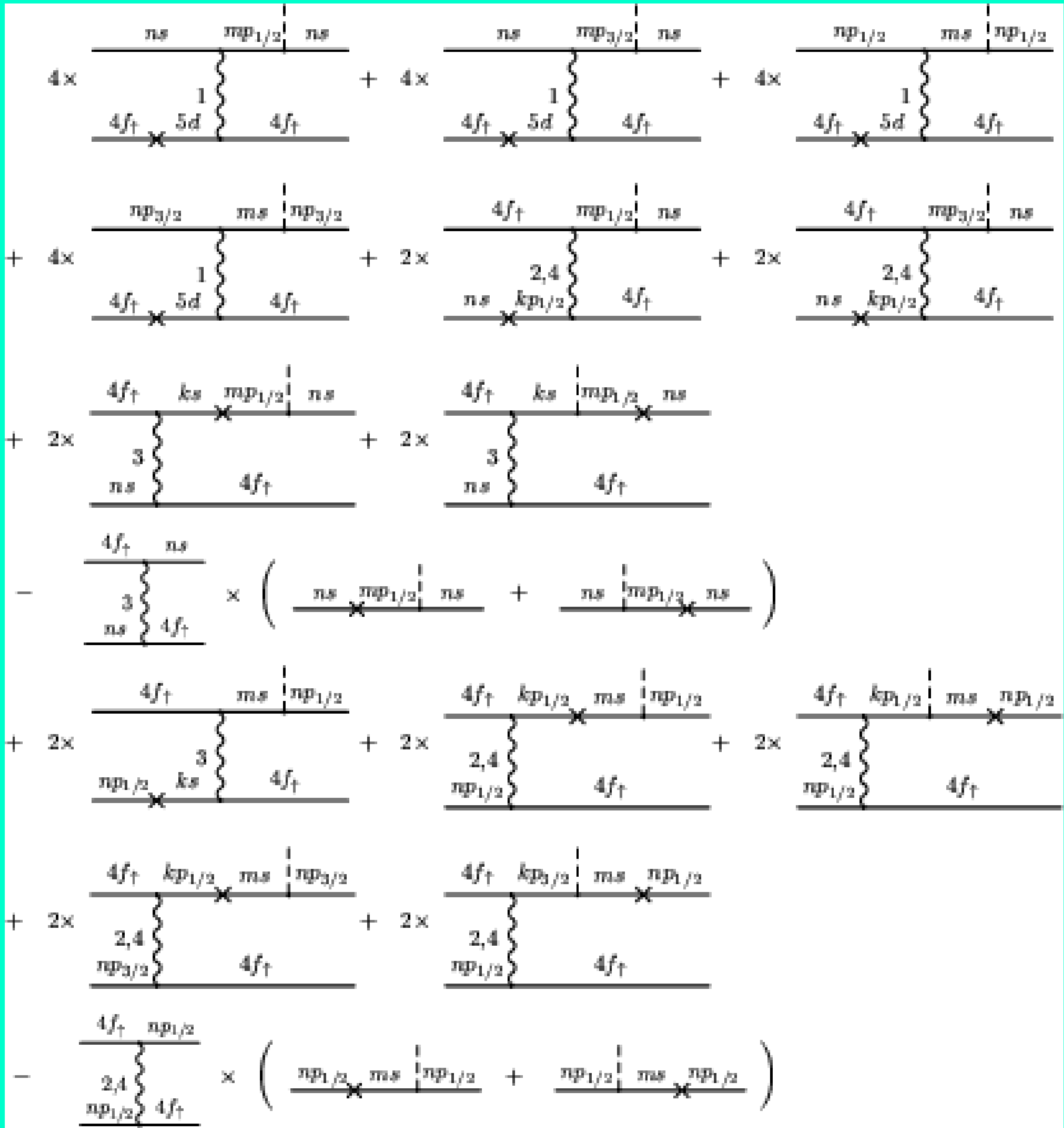



Diagramatic notation for influence of the displacement on external orbitals of Rare Earth ion

There is also a residual (noncentral) Coulomb intreraction between electrons

There are 15 many-body diagrms that contribute to the constant A.

$$\delta\varepsilon = -A \times 27.2eV \times \left( \frac{d_e}{ea_B} \right) \times \left( \frac{\vec{x} \cdot \vec{S}}{a_B (7/2)} \right)$$



| NP | P |
|---|---|
| A= | A= |
| -0.094 | -0.008 |
| -0.159 | -0.016 |
| +0.080 | -0.006 |
| +0.133 | -0.010 |
| +0.141 | +0.186 |
| -0.295 | -0.596 |
| -0.257 | -0.614 |
| -0.040 | -0.049 |
| +0.610 | +0.010 |
| -0.295 | +0.671 |
| -0.009 | -0.189 |
| -0.001 | -0.019 |
| +5.055 | -0.656 |
| -4.615 | +1.396 |
| -0.159 | -0.005 |
| =0.095 | =0.095 |

**An experimental estimate for x in $Eu_{0.5}Ba_{0.5}TiO_3$ is**

$$x \sim 0.01\ \text{Å}$$

**Together with the calculated value of A this gives the effective electric field**

$$E_{eff} \sim 10\,\text{MV/cm}$$

# Conclusions

1) The electron EDM experiment with $Eu_{05}Ba_{05}TiO_3$ is on the way.

2) The expected improvement of sensitivity compared to the present level is at least factor 10.

3) Presently we have only an estimate of the effect. An accurate theoretical calculation is necessary.

4) The crystal structure (displacements of ions) is a crucial input in the theory.

5) The structure has to be determined in neutron/X-ray/NQR/Mossbauer measurements.