Measuring the Electron's Electric Dipole Moment using trapped PbF molecules

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An electron EDM is a great place to look for physics beyond the standard model.

Hinds, Physica Scripta, T70 34 1997

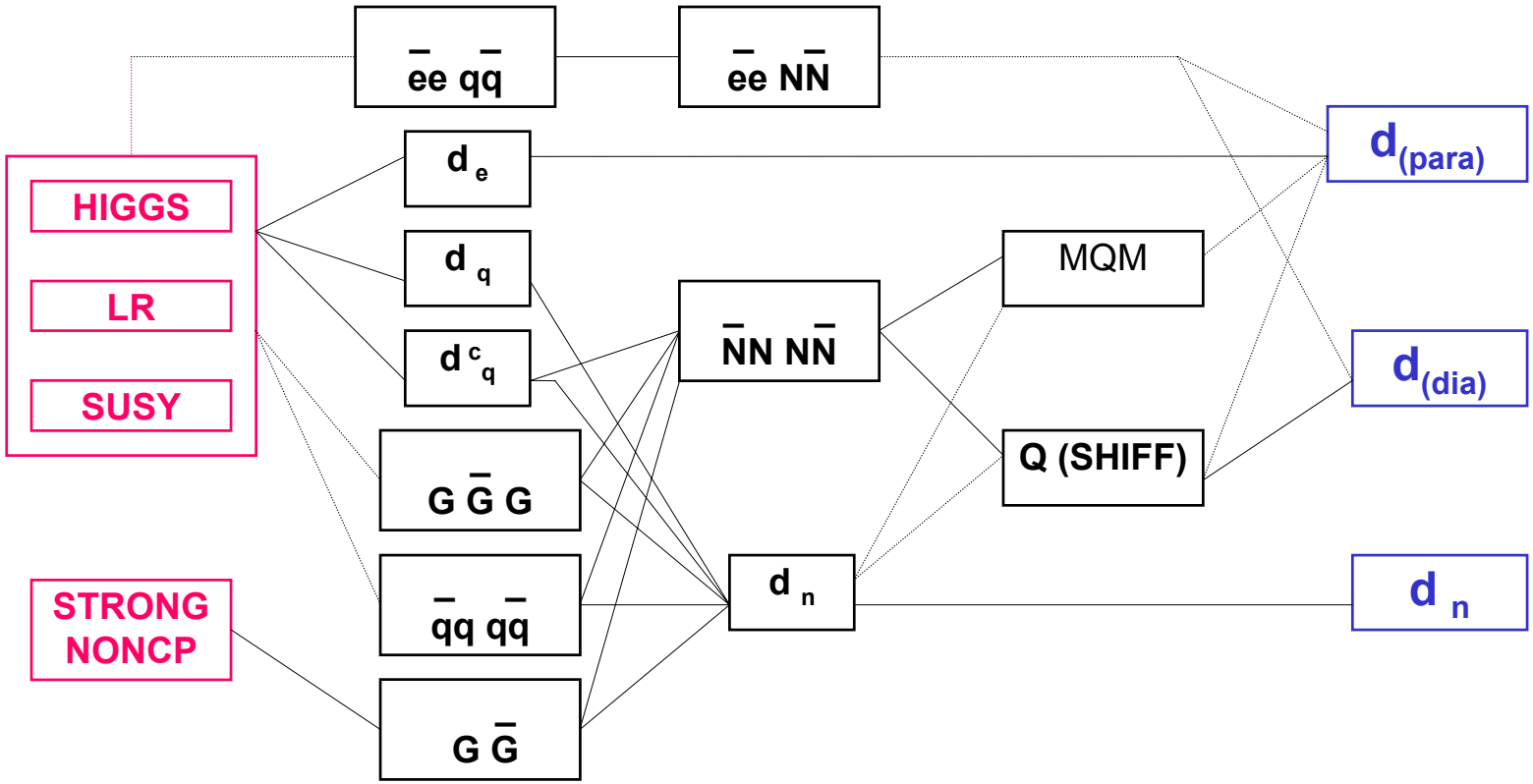
Type of Model	Electric Dipole Moment (e cm)
Standard Model	$<10^{-38}$
Supersymmetry	$<10^{-27}$
Left-right symmetric models	10^{-28}-10^{-26}
Lepton-flavour changing models	10^{-29}-10^{-26}
Higgs model	10^{-28}-10^{-27}

Current limit $<1.6 \times 10^{-27}$

*Regan, Commins, Schmidt, DeMille, PRL **88** 71805 2002*

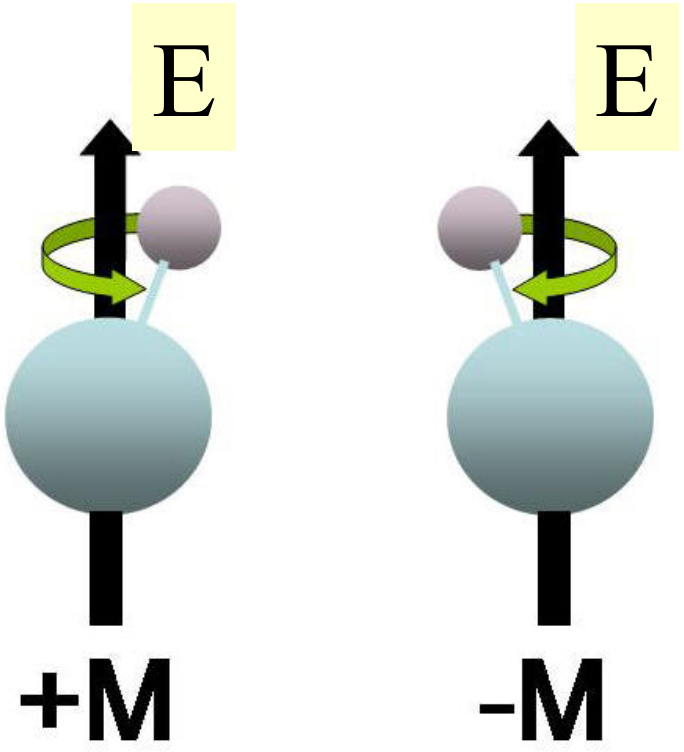
Theories of CP-violation to experiment

Fundamental Theory	CP violating interactions	Nucleon-nucleon & nucleon-electron interactions	Nuclear structure	Atomic & molecular structure



The current limit $d_e < 1.6 \times 10^{-27}$ e•cm has already discounted many variants of Supersymmetry

CP symmetry implies that for ANY atom or molecule states with nonzero angular momentum M along an electric field axis are doubly degenerate.



To search for $\not{CP}$ look for

$\Delta U = U_{+M} - U_{-M}$

in a strong E field.

Difficulty:
A background magnetic field mimics an EDM.

HEAVY PARAMAGNETIC MOLECULES ARE EXTRAORDINARILY SENSITIVE TO $\not{CP}$ CAUSED BY AN ELECTRON EDM

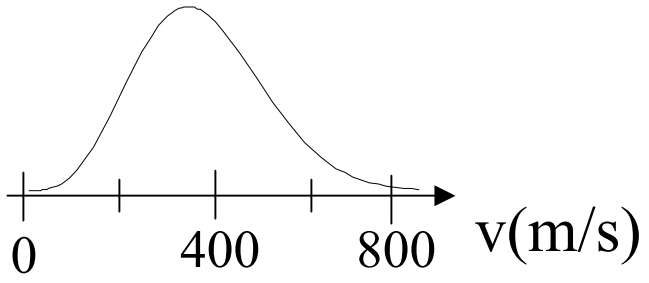
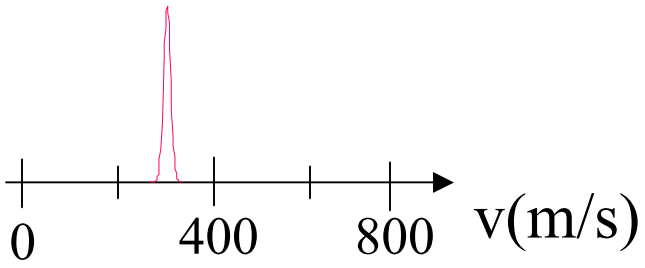
At $d_e < 1.6\times10^{-27}$ e cm (The Commin's Tl limit[#]). . .

System	E-field	EDM shift	Equiv B
Tl($^2P_{1/2}$ F=1)	100 kV/cm	0.02mHz	24pG
Cs($^2P_{1/2}$ F=3)	100 kV/cm (assumed)	0.004mHz	6.3pG
PbF ($X^2\Pi_{1/2}$, J=1/2, F=1)	4.8 kV/cm	17mHz	88,000 pG

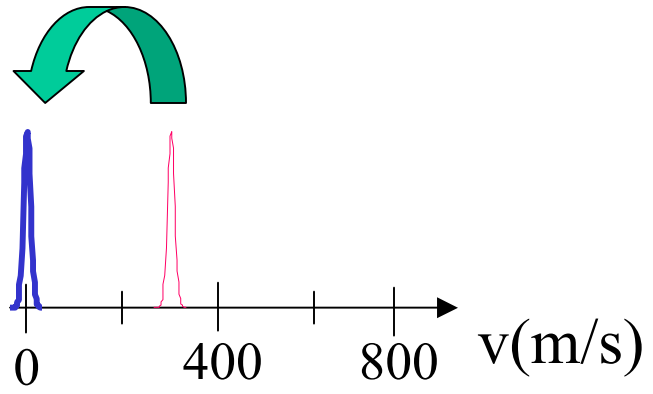
In principle, PbF should be ~ 3 orders of magnitude more sensitive to an electron EDM than a Tl or Cs based experiment.

[#] *(PRL **88** 71805 2002)*

Differences between a Tl and PbF beam

Beam	Expected Flux	Speed Distribution
Tl(F=1,|M|=1) (from oven)	8×10^{15}/str/sec	
PbF(J=1/2, F=1,|M|=1) (from supersonic expansion)	6×10^{10}/str/sec	

To fully realize the advantages of its sensitivity, we must work with trapped PbF.

PbF(J=1/2, F=1,|M|=1) (from supersonic expansion)	6×10^{10}/str/sec	

Before we carry out an EDM measurement we must:

1. Decelerate our molecular beam
2. Trap PbF
3. Cool PbF with laser cooled Rb

DECELERATION OF LIGHTER, LESS ENERGETIC MOLECULES HAS BEEN ACHIEVED WITH A TRAVELING POTENTIAL WELL

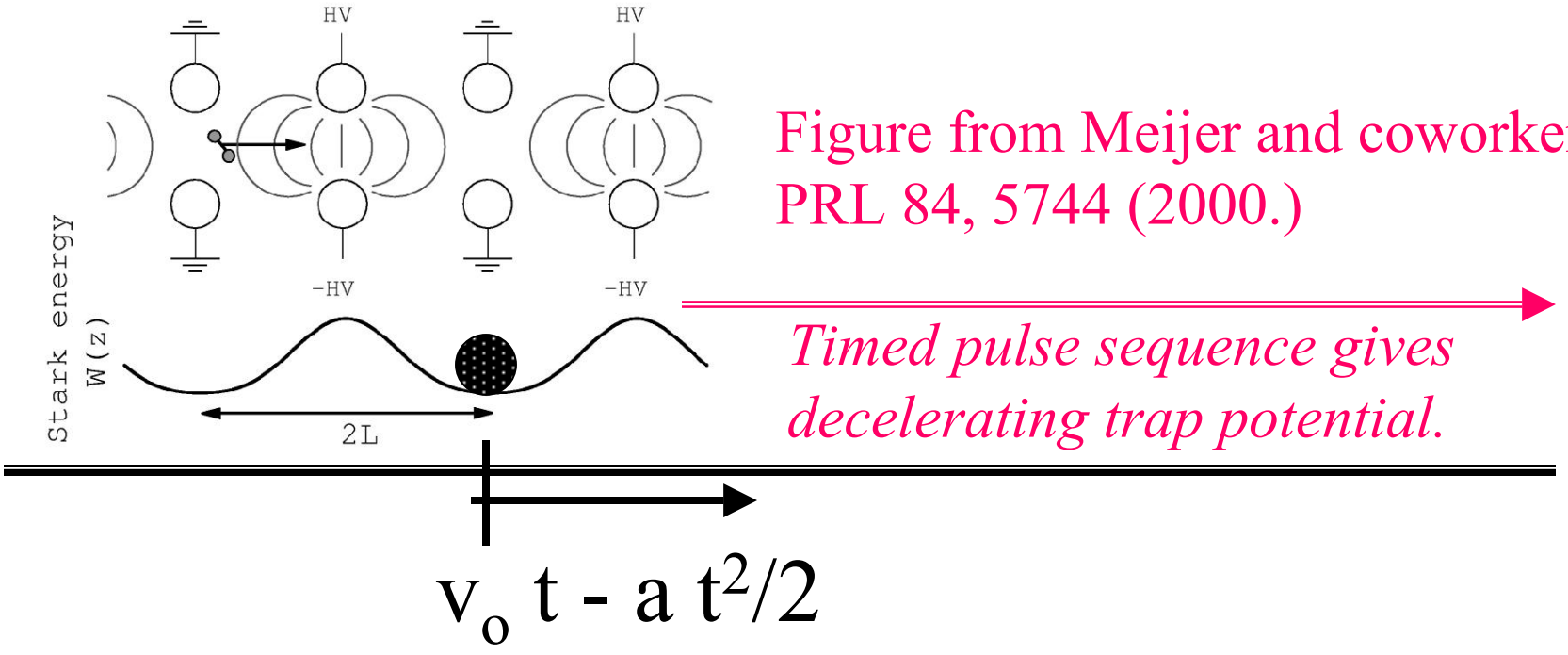


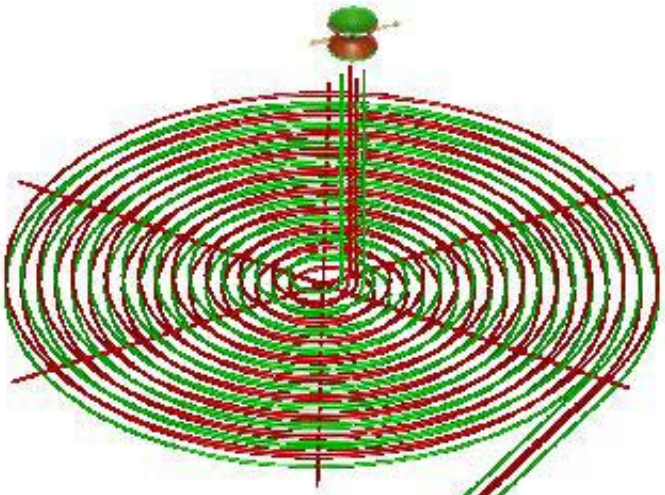
Figure from Meijer and coworkers, PRL 84, 5744 (2000.)

Timed pulse sequence gives decelerating trap potential.

PROBLEM: *Need make a traveling potential well.*

Well depth ~0.1K implies number of electrodes needed ~10,000

Turbo Molecular Stark Cooler



Decelerating trap

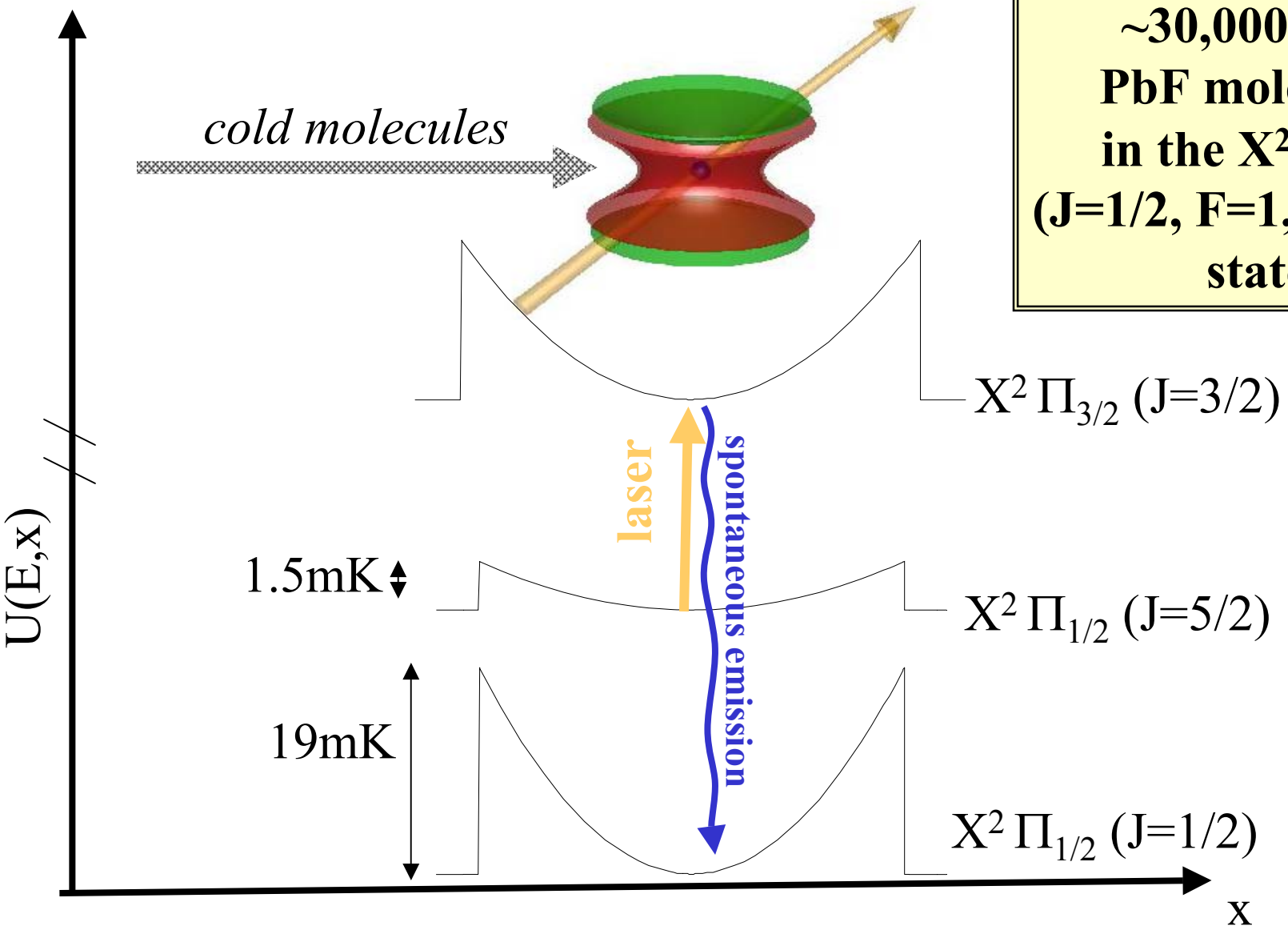
Spinning wires

Quadrapole Guide

Cold fast moving molecules

STEP #3: Dark State Trap Molecules

Load rate:
~30,000/sec
PbF molecules
in the $X^2\Pi_{1/2}$
(J=1/2, F=1, $|M_F|$=1)
state

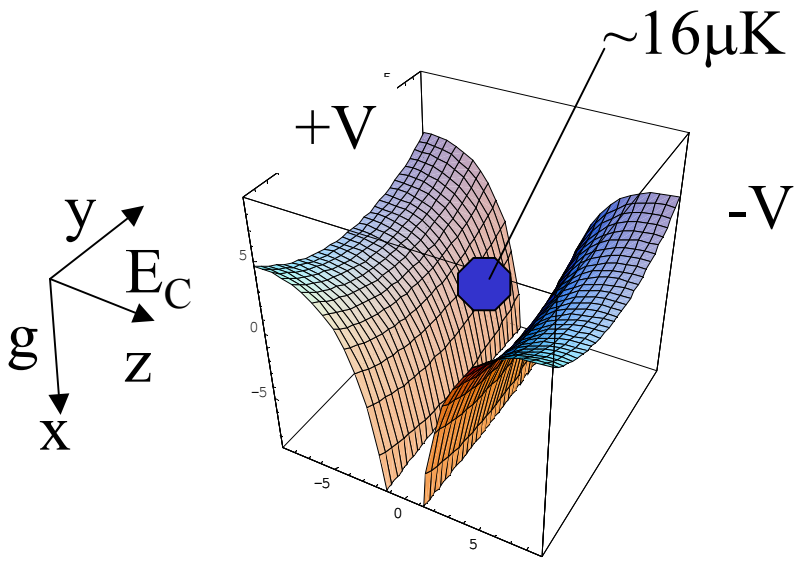


Result of Cooling and Trapping

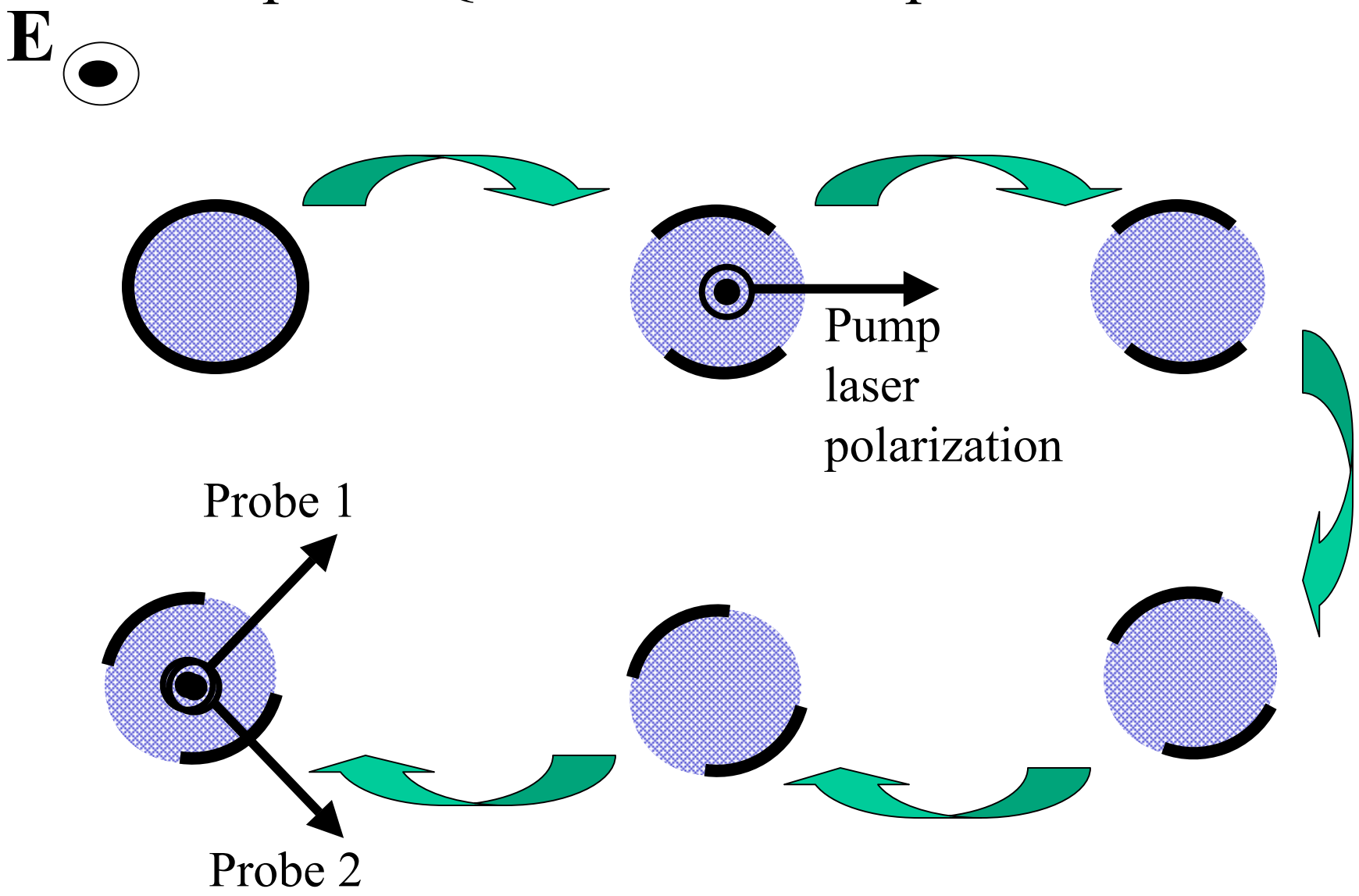
250,000 PbF ($^2\Pi_{1/2}$ (F=1,$|M_F|$=1, 50% J=1/2, 50% J=3/2))

molecules at 16 μK in a

biased Stark - gravitational trap.



Optical Quantum Beat Experiment



Terms Effecting EDM Rotational Frequency:

For a given particle i moving in the trap the $\vec{E}$ and $\vec{B}$ fields depend on time, and so must the energy difference between $+M_F$ and $-M_F$ states:

$$\gamma_i(t) = \frac{\Delta U_i}{h} = \frac{1}{2\pi}\frac{d\phi_i}{dt}$$

$$= \left[\alpha_i \hat{E} \bullet \vec{B} + \frac{\Delta M_F}{2\pi} \frac{\hat{z} \bullet (\vec{E} \times \dot{\vec{E}})}{E^2} + d_{EDM} \eta_i \right]$$

EDM

Zeeman interaction

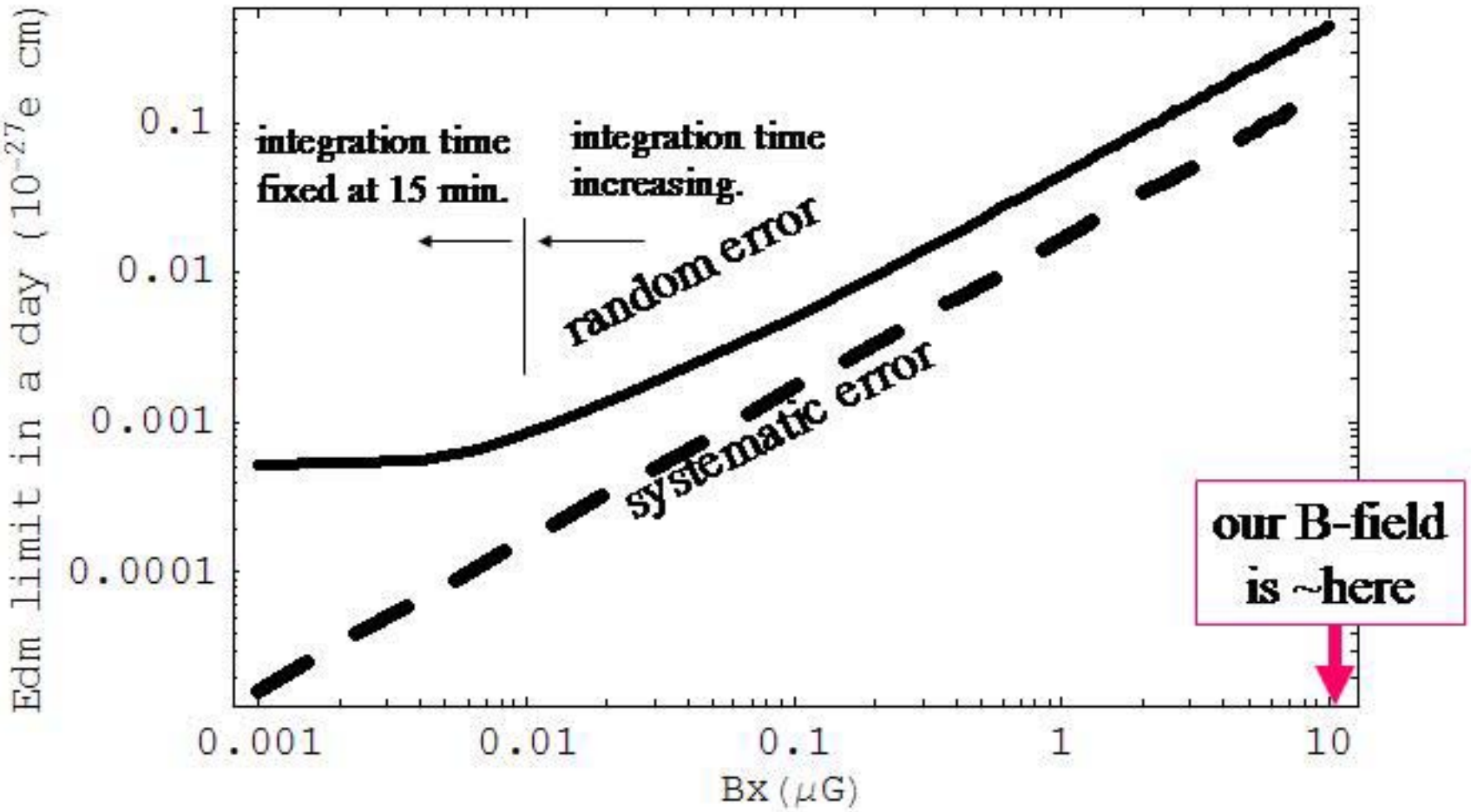
geometric phase

TO DISTINGUISH AN EDM ROTATION FROM A ZEEMAN ROTATION, J=1/2 AND J=3/2 STATES WILL BE USED.

quantity	J=1/2	J=3/2	units
η	11.8	3.4	mHz/(10^{-27} e-cm)
α	187	203	mHz/μG
$\tilde{\alpha}$	–86	–185	mHz/μG
$\tilde{T} = \frac{\tilde{U}}{k_B} = \frac{1}{k_B}\frac{\partial U}{\partial E_o}E_o$	23	23	mK
$\nu_g = \frac{g}{2\pi}\left(\frac{m}{3\tilde{U}}\right)^{1/2}$	0.977	0.977	Hz
$d_g = \frac{\tilde{U}}{mg}$	87	87	mm

Experimental parameters, PbF $^2\Pi_{1/2}$ (J,F=1,$|M_F|$=1) at 4.3 kV/cm

EXPECTED EDM LIMIT IN A DAY



Measuring an EDM with PbF molecules slowed by a Turbo Molecular Stark Cooler

1. Molecular trap allows for a sensitive EDM measurement with limited statistics.

2. Three orders of magnitude increase in sensitivity to an electron EDM over an atomic experiment.

3. Three orders of magnitude less sensitivity to magnetic fields than comparable atomic experiments.

4. Zero applied magnetic field creates a situation for which a likely EDM dipole moment from theories beyond the standard model will dominate our measurement.