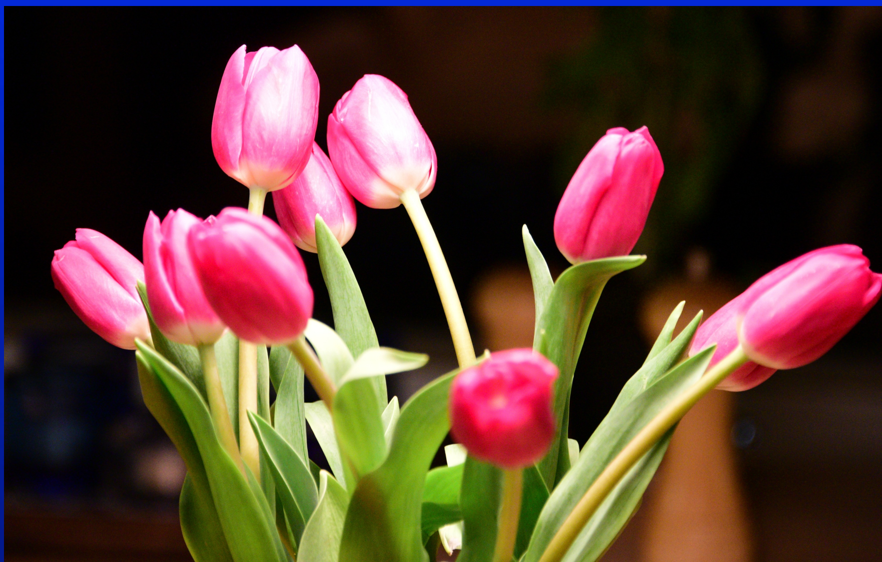
Quantum mechanics of the neutron electric dipole moment



Gordon Baym
University of Illinois

Celebrating **Peter Braun-Munzinger** at 70

QCD thermodynamics: pressure and passion
Schloss Waldthausen
25 August 2016

Volume 190, number 1,2 PHYSICS LETTERS B 21 May 1987

TRANSVERSE ENERGY PRODUCTION IN PROTON–NUCLEUS AND NUCLEUS–NUCLEUS COLLISIONS ☆

Gordon BAYM [a], Peter BRAUN-MUNZINGER [b] and Vesa RUUSKANEN [a,c]
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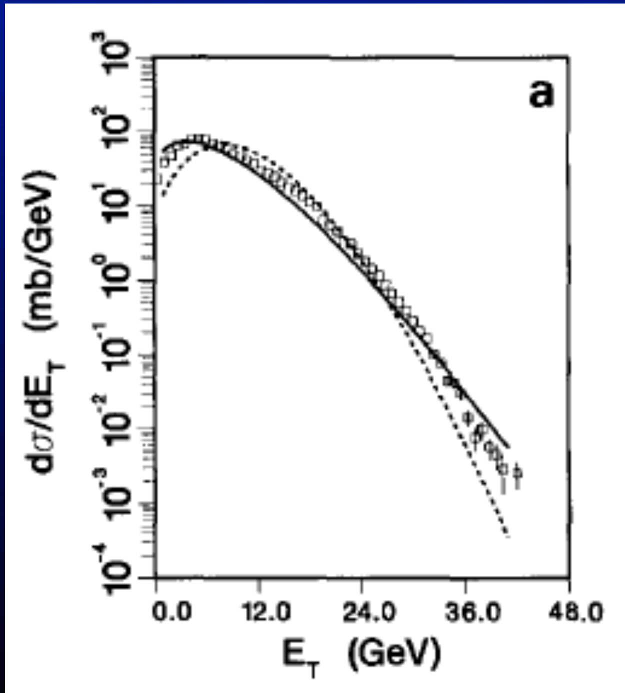
[b] *Physics Department, State University of New York, Stony Brook, NY 11794, USA*
[c] *Department of Physics, University of Jyväskylä, Seminaarinkatu 15, SF-40100 Jyväskylä, Finland*

Vesa -2006

importance of rescattering in the target fragmentation region in the measured E_T spectra.

$$\frac{1}{N}\frac{dN}{dE_T} = \frac{1}{\epsilon_0} e^{-E_T/\epsilon_0} \sum_{n=1}^{\infty} \frac{\bar{n}^n}{n!((n-1)!} e^{-\bar{n}} \left(\frac{E_T}{\epsilon_0}\right)^{n-1}$$

In conclusion, the HELIOS experiments provide strong evidence for rescattering of secondaries in the nucleus. The gross features of transverse energy production in ^{16}O–Pb scattering can be understood in terms of independent nucleon scatterings on the target. However, when larger projectiles are used we expect significant deviations, in central collisions, from the independent nucleon scattering picture.



G. Baym, S. Nagamiya, and P. Braun-Munzinger, eds. Proc. 7th Int. Conf. on Ultrarelativistic nucleus-nucleus collisions (Quark Matter '88), Nucl. Phys. A498 (1989)

ELSEVIER
Nuclear Physics A610 (1996) 286c–296c
NUCLEAR PHYSICS A

Physics of Coulomb Corrections in Hanbury-Brown Twiss Interferometry in Ultrarelativistic Heavy Ion Collisions

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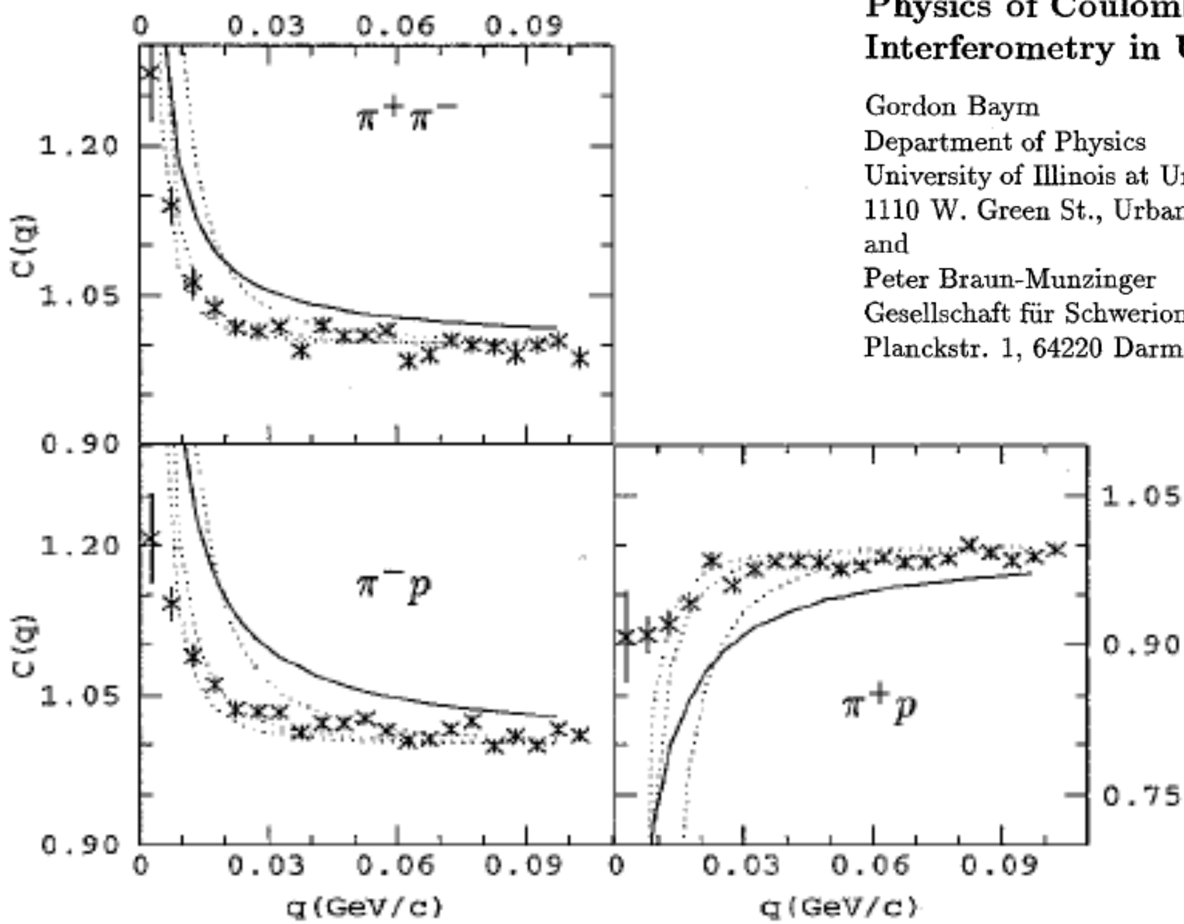
Peter Braun-Munzinger
Gesellschaft für Schwerionenforschung (GSI)
Planckstr. 1, 64220 Darmstadt, GERMANY



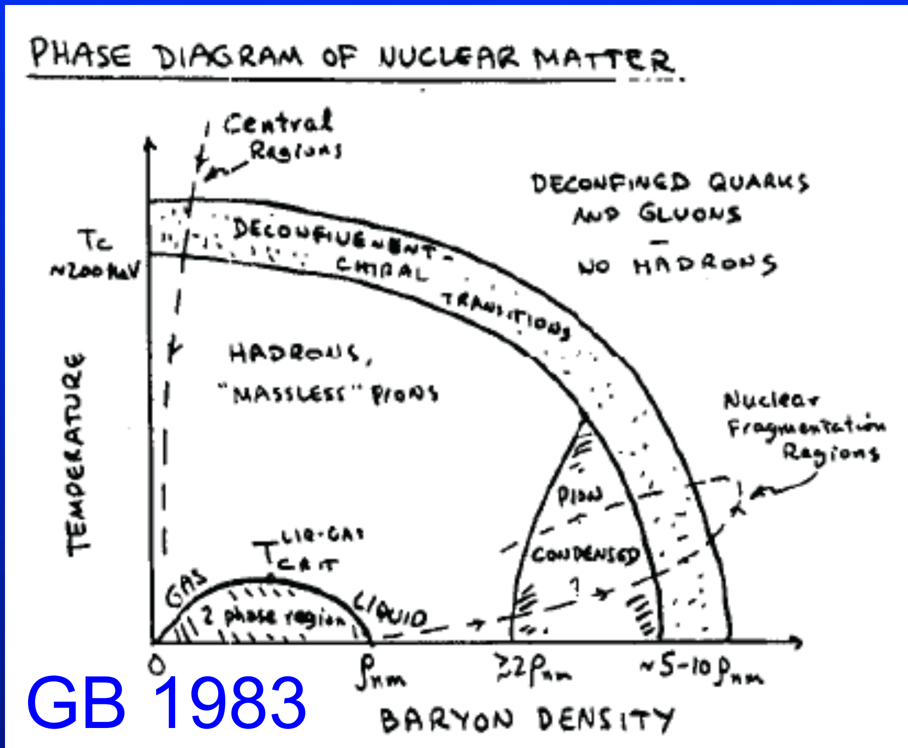
Calculate Coulomb corrections in classical toy model

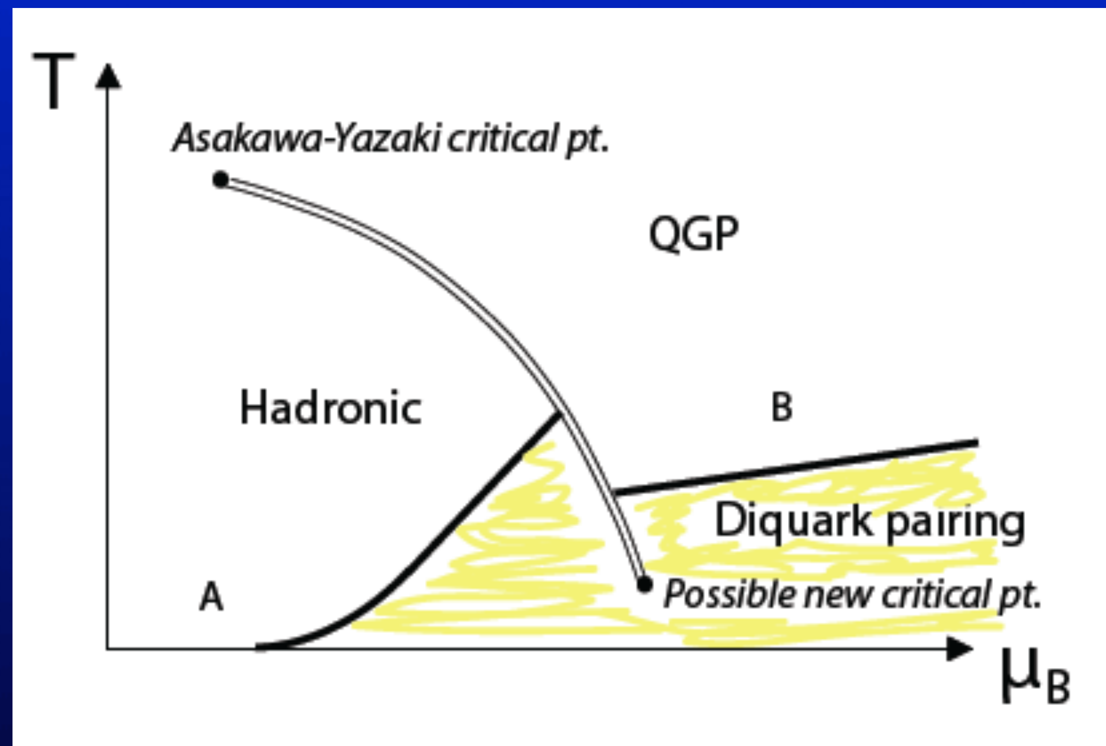
$$\frac{q^2}{2m_{red}} = \frac{q_0^2}{2m_{red}} \pm \frac{e^2}{r_0}$$

Correction of correlation fcn

$$C(\vec{q}) = \frac{q_0}{q} C_0(\vec{q}_0) = \left(1 \mp \frac{2m_{red}e^2}{r_0 q^2}\right)^{1/2} C_0(\vec{q}_0)$$

The QCD phase diagram





After long arguments with Peter and Johanna at the 2015 Kobe QM meeting

Jaipur 2007

Trento 2003

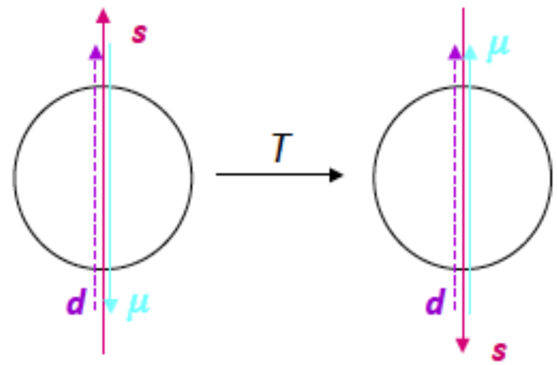
Urbana 2015

The neutron electric dipole moment

The neutron electric dipole moment

T Violation and Neutron EDM

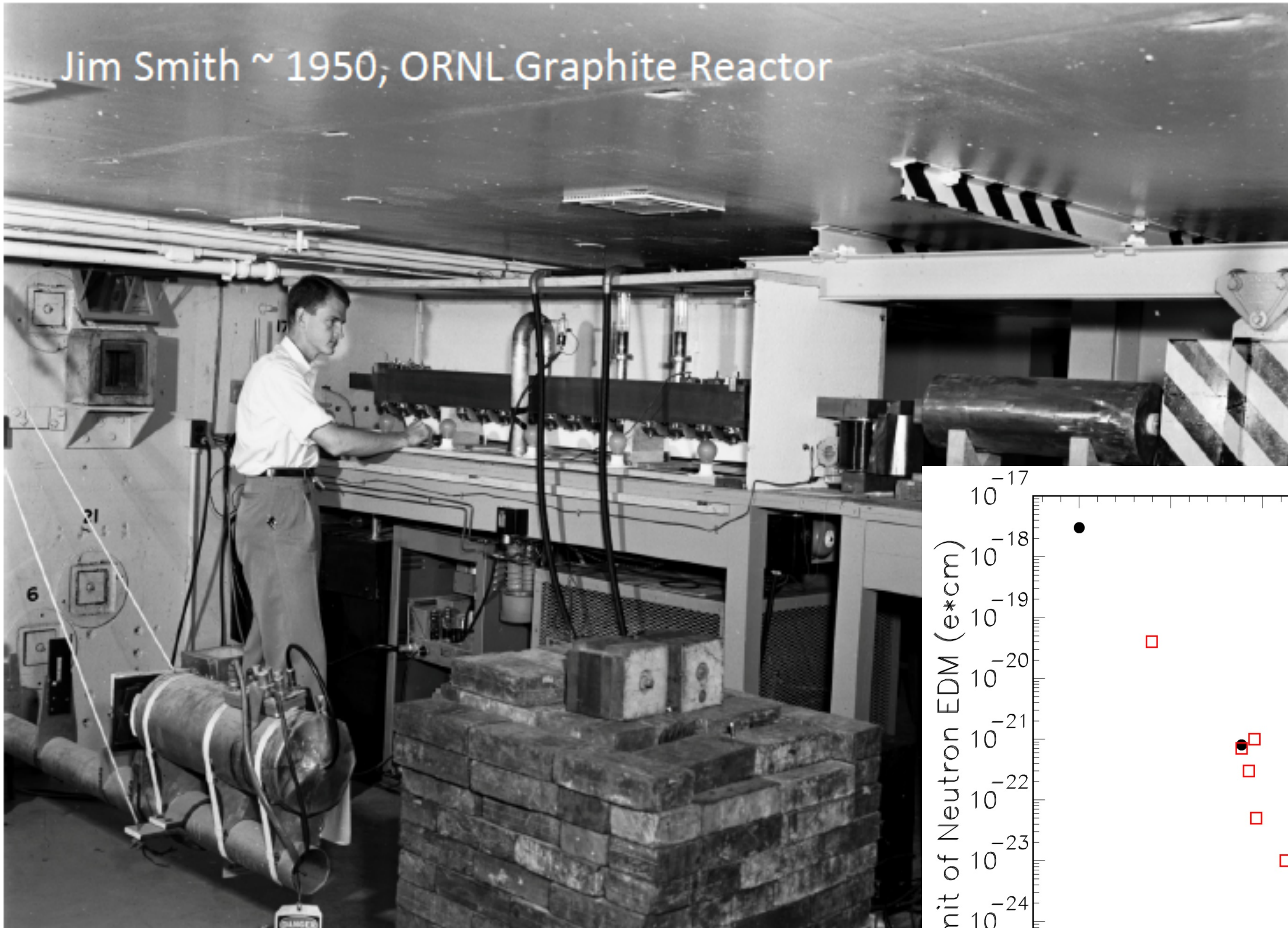
- Existence of particle EDM implies T reversal sym'y violation
  - spin is only orientation (vector) in problem: $\vec{d} \uparrow\uparrow \vec{s}$ or $\vec{d} \uparrow\downarrow \vec{s}$

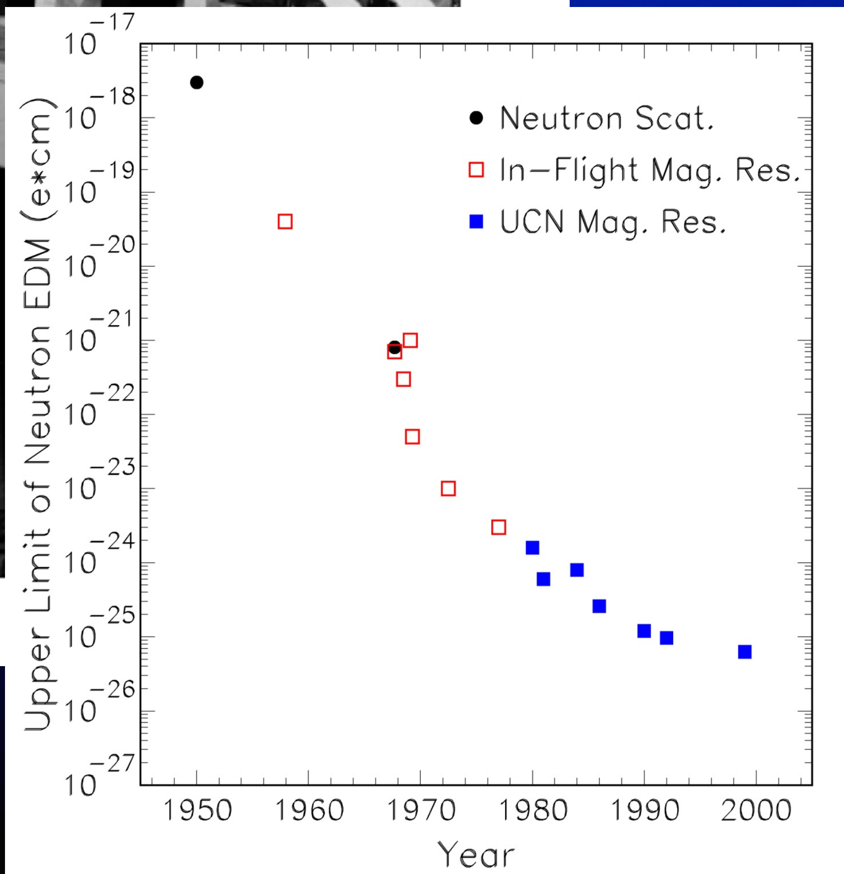


- T reversal violation implies CP violation if CPT symmetry preserved
  - *observation*; requires only locality, Lorentz invariance and Hermitian Hamiltonian
- Not enough standard model CP violation to explain baryon asymmetry of universe
- Generic scale of neutron EDM in SUSY above current limit

Doug Beck – Mar. 30, 2015 in Urbana

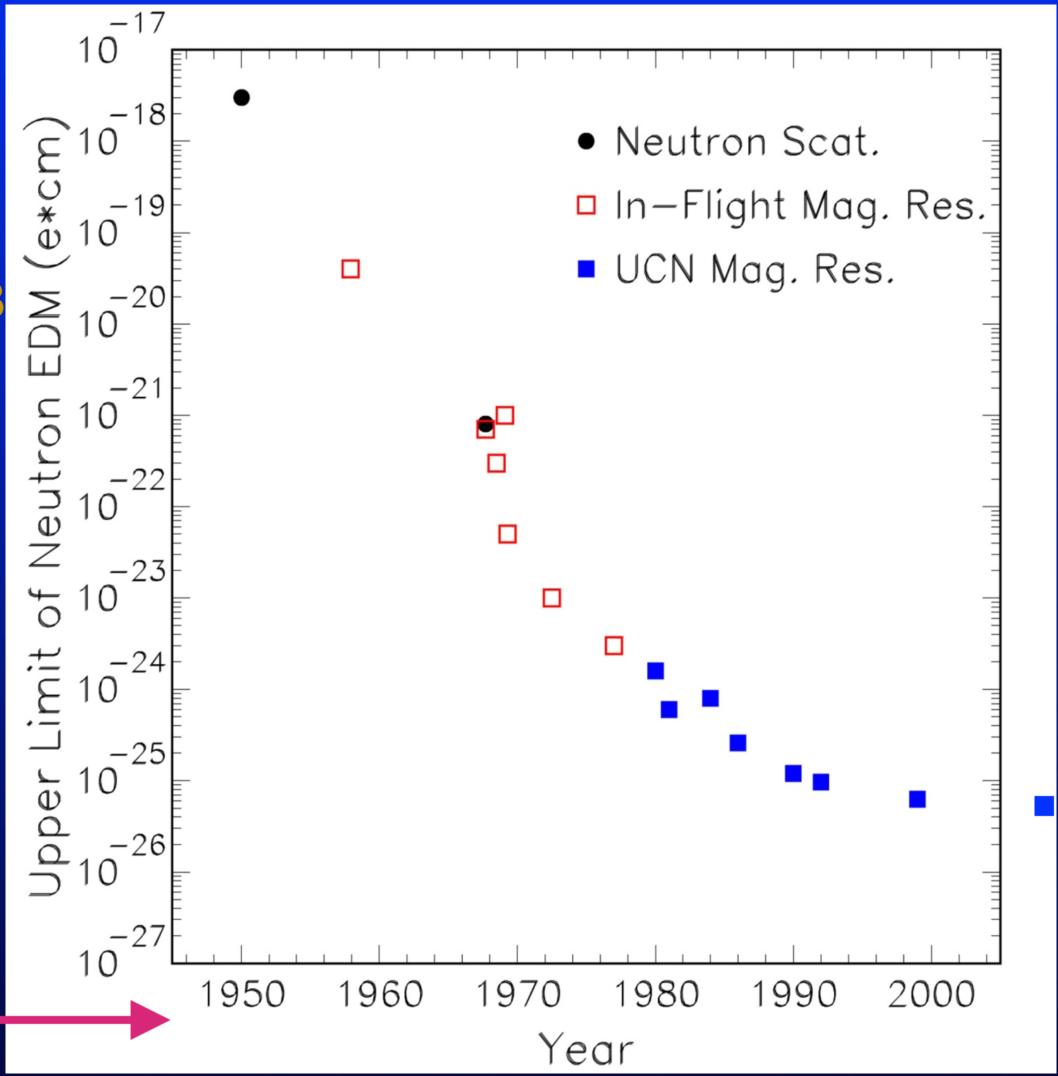
EDM Measurements





EDM measurements

- Neutron
  - Sussex, RAL, ILL
  - $d_n < 2.9 \times 10^{-26}$ e·cm
    Baker, et al. PRL **97** (2006) 1318
  - [$d_n < 5.5 \times 10^{-26}$ e·cm]
    Serebrov, et al. arXiv:1408.6430
  - Future
    - Sussex, RAL, ILL
    - Crystal ILL
    - Gatchina ILL
    - PSI
    - *SNS Oak Ridge*
    - $d_n < 5 \times 10^{-28}$ e·cm?
    - Japan
    - TRIUMF
    - *TU Munich*



EDM measurements

- Electron
  - paramagnetic atoms: Tl Regan, et al. PRL **88** (2002) 071805
    - $d_e < 1.6 \times 10^{-27}$ e·cm
  - molecules:
    - YbF $d_e < 1.05 \times 10^{-27}$ e·cm Hinds, et al. Nature **473** (2011)
    - ThO $d_e < 8.7 \times 10^{-29}$ e·cm J. Baron, et al. Science **343** (2014) 269
- Nuclei
  - Hg Griffiths, et al. PRL **102** (2009) 101610
    - $d_{Hg} < 3.1 \times 10^{-29}$ e·cm
  - [Ra trapped atom: ANL]
  - [p, d storage ring proposal: BNL]

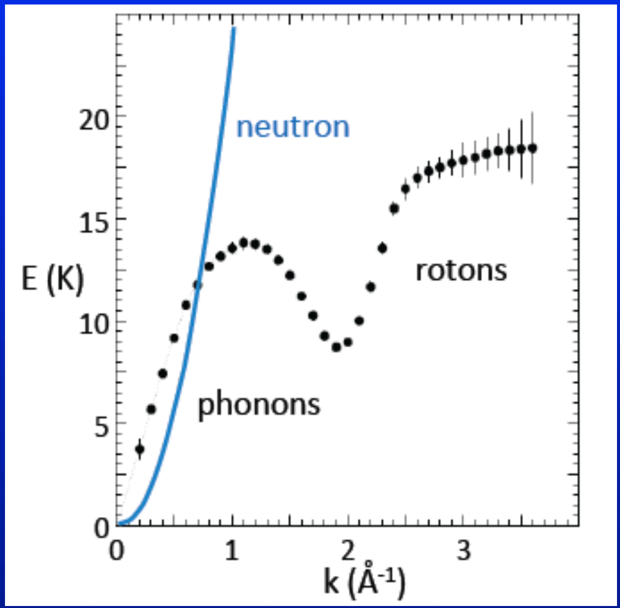
Oak Ridge SNS experiment: T = 0.5 K

Concept: Golub and Lamoreaux, Phys. Rep. 237 (1994) 1

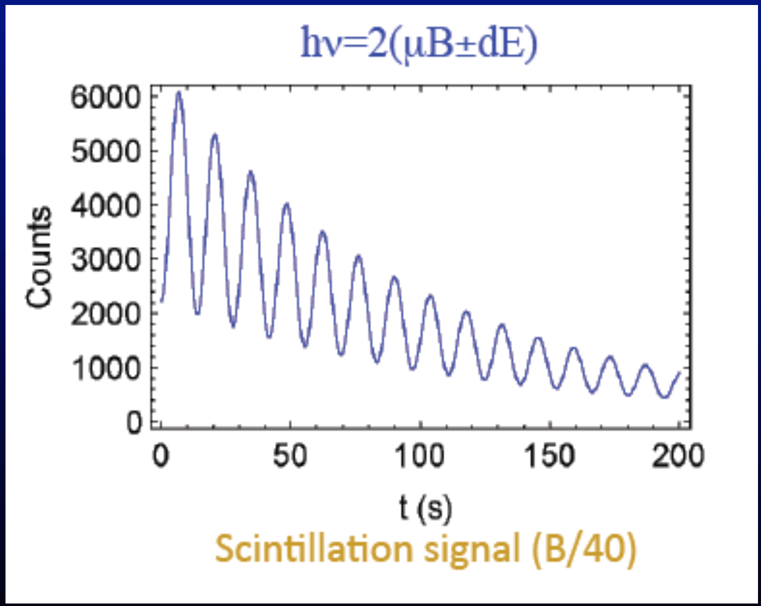
Spin-polarized ultracold neutrons on spin-polarized ^3He:

n + ^3He -> p + t + 764 KeV

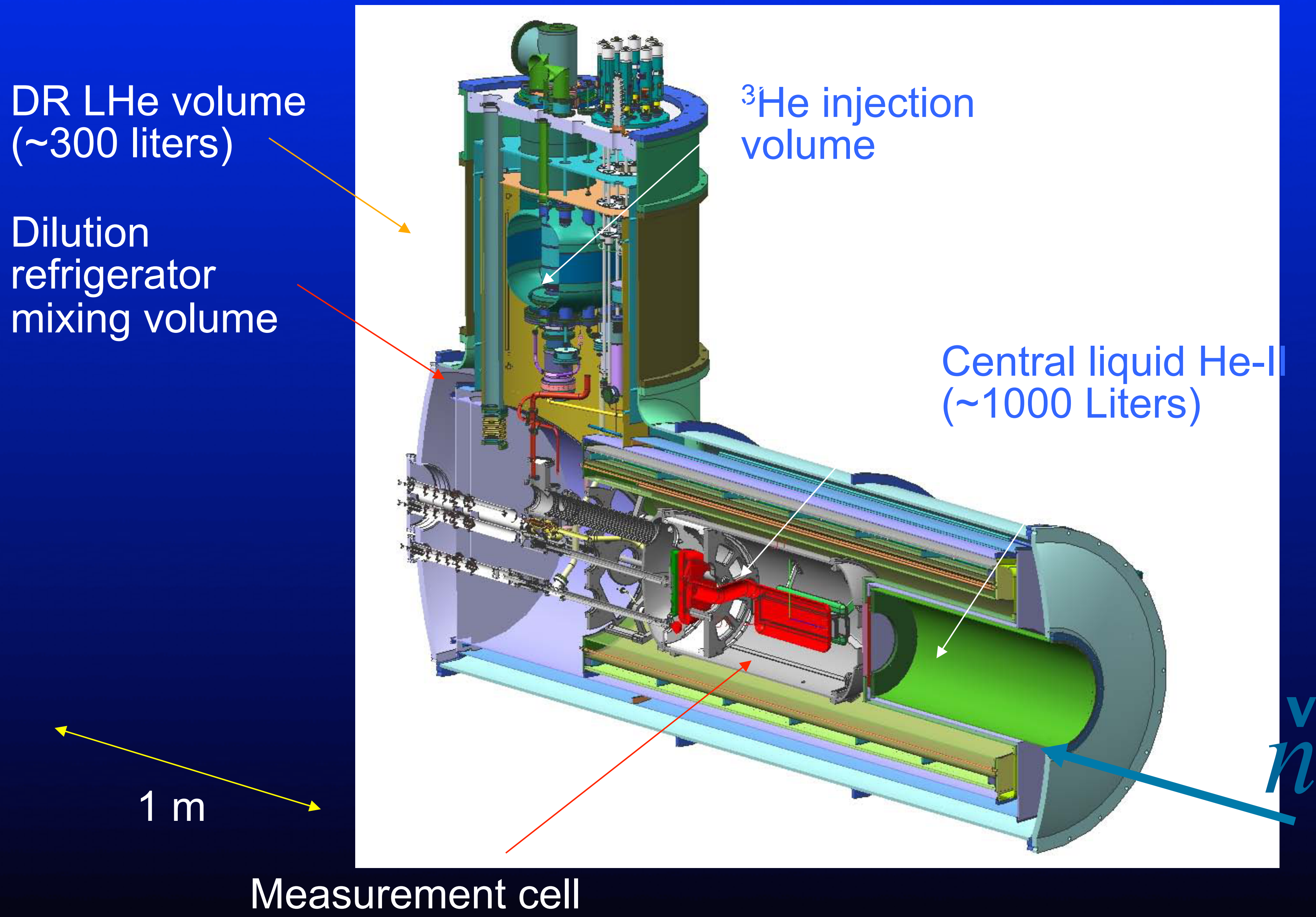
$\sigma(\vec{n} + {}^3\vec{He}) \sim 0$, $\sigma(\vec{n} + {}^3\overleftarrow{He}) \sim 2$mb



- Measure neutron precession frequency in “NMR” experiment;
- look at modulation from external electric field coupled to nEDM



Apparatus Overview



Quantum mechanics of neutron dipole moment

GB and D.H. Beck, PNAS, 113, 7438 (2016)

"A parity-violating perturbation, corresponding physically to a permanent electric dipole moment of an electron parallel to its spin, is introduced into the Dirac equation for an electron."

E. Salpeter, PR 112 (1968)

$$\left[\left(p_\mu + \frac{e}{c}A_\mu\right)\gamma_\mu - imc\right]u = -\xi\left(\frac{e\hbar}{4mc^2}\right)\gamma_5\gamma_\mu\gamma_\nu F_{\mu\nu}u.$$

The neutron EDM must point along the spin, since the spin is the only vector in the neutron. TRUE OR FALSE???

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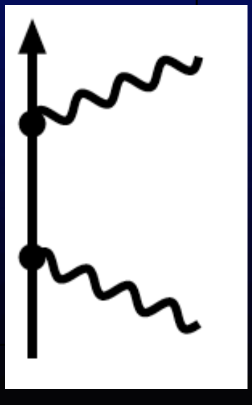
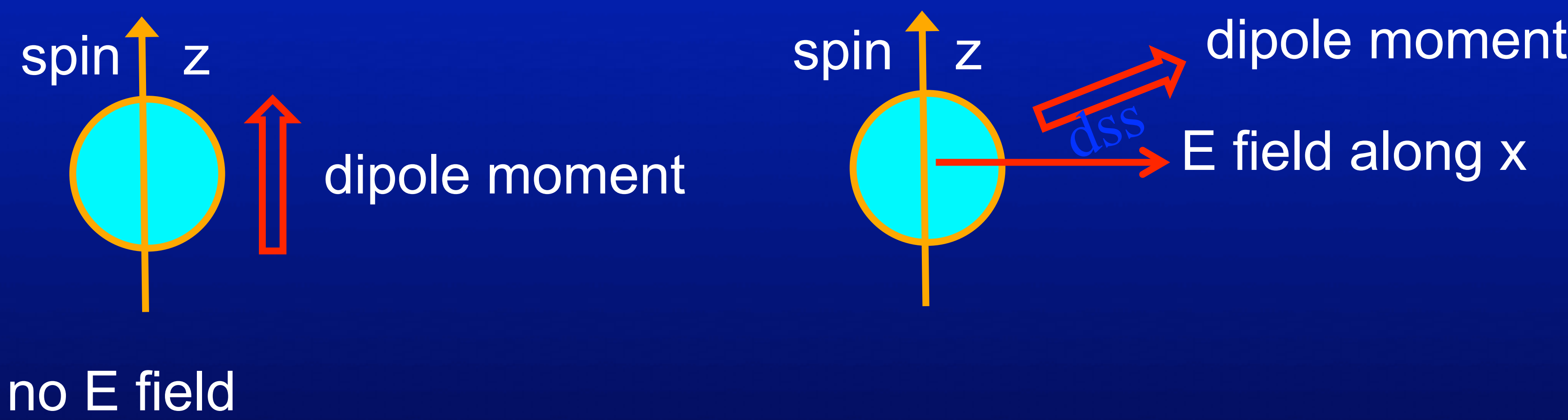
The nEDM cannot be locked to spin, since neutron can be polarized by external electric field

Spin operator and dipole operator are non-commuting indepent operators.



Dipole moment = polarizability X electric field
Polarizability measured in Compton scattering on n.

Puzzle: put neutron is very strong magnetic field along z, locking in spin. Apply electric field along x. Induce dipole moment along x, not parallel to spin!



Ground state of the neutron in presence of CP = T violation

$$|N\uparrow\rangle = |\uparrow\rangle + \eta|(t)\uparrow\rangle$$

$|\uparrow\rangle$ = familiar ground state

$|(t)\uparrow\rangle$ = odd parity spin ½ excited state of neutron

η = very small < 10-12

Lowest odd-parity excited neutron states: spin 1/2 = N(1535)
spin 3/2 = N(1520)

Electric dipole moment: $\vec{\mathcal{D}} \sim \int d^3r\, \vec{r} \sum_{quarks,i} Q_i \bar{q}_i(\vec{r})\gamma_0 q_i(r)$

$$\langle \vec{d}_n \rangle = e\langle N\uparrow|\vec{\mathcal{D}}|N\uparrow\rangle = e\eta\langle\uparrow|\vec{\mathcal{D}}|(t)\uparrow\rangle + c.c.$$

Spin: $\langle \vec{S} \rangle = \langle N\uparrow|S_z|N\uparrow\rangle = \frac{1}{2}\hat{z}.$ => $\langle \vec{d}_n \rangle = d_n\hat{z} = \langle \vec{S} \rangle$

Wigner-Eckart theorem at work (in absence of applied fields).

Response of neutron to external electric field

In weak external electric field $\tilde{\mathrm{E}}$ state of neutron is:

$$|(E)N\uparrow\rangle = |N\uparrow\rangle + e\mathcal{V}\vec{\mathcal{D}}\cdot\vec{E}\,|N\uparrow\rangle$$

where $\mathcal{V} = \sum_{n\neq\uparrow}\frac{|n\rangle\langle n|}{\omega_n}$ with $|\mathrm{n}\rangle$ = odd parity states.

Field mixes in spin 1/2 and 3/2 $\mathcal{D}_z|\uparrow\rangle = \frac{1}{3}\langle\vec{\mathcal{D}}^{\,2}\rangle^{1/2}\left(\sqrt{2}\,|(d)3/2\rangle - |(d)1/2\rangle\right)$

Total dipole moment: $\langle\vec{d}_{tot}\rangle = d_n\hat{z} + \chi_n\vec{E}$

Electric polarizability: $\chi_n = 2e^2\langle\uparrow|\mathcal{D}_z\mathcal{V}\mathcal{D}_z|\uparrow\rangle = \frac{2e^2}{9}\langle\vec{\mathcal{D}}^{\,2}\rangle\left(\frac{1}{\omega_{1/2}} + \frac{2}{\omega_{3/2}}\right)$

Experimentally $\chi_n = 1.26\times10^{-3}\ \mathrm{fm}^3$ *J. Schmiedmayer, et al. PRL (1993)*
B. Holstein and A. Nathan, PRD (1994).

so that $\langle\vec{\mathcal{D}}^{\,2}\rangle \simeq 0.77\,\mathrm{fm}^2$

Neutron has big dipole moment jiggling inside, with tiny <d>, cf. hydrogen atom in ground state.

How can the dipole moment not be parallel to the spin?

Wigner-Eckart theorem: in absence of external (e.m.) fields, in eigenstate of total angular momentum, J and J_z ,
<EDM> parallel to <spin>.

Lorentz invariance: neutron in absence of external fields is spin ½ with only single axis.

How can an E electric field => dipole moment not parallel to the spin?

Admixture of spin-3/2 => n has multiple axes.

Imagine state in the presence of E and η is pure spin-1/2.
Transverse electric field mixes in S_z= -1/2 components of the excited states, neutron no longer an eigenstate of S_z.

Wigner-Eckart theorem does not apply. Spin and induced EDM need not be parallel.

Response of neutron to E and B fields

Coupling to external fields: $H_{em} = -\vec{\mu}_n \cdot \vec{B} - e\vec{\mathcal{D}} \cdot \vec{E}$

Eq. of motion of spin: $\frac{d}{dt}\vec{S} = -i[\vec{S}, H_{em}] = 2\mu_N \vec{S} \times \vec{B} + e\vec{\mathcal{D}} \times \vec{E}$

Thus

$$
\begin{aligned}
\frac{d}{dt}\langle\vec{S}\rangle &= 2\mu_N \langle\vec{S}\rangle \times \vec{B} + \langle\vec{d}_{tot}\rangle \times \vec{E} \\
&= 2\langle\vec{S}\rangle \times (\mu_n \vec{B} + d_n \vec{E})
\end{aligned}
$$

For spin 1/2 induced edm does not enter because polarizability tensor is ~ unit matrix.

Not so for higher spin particles, e.g., ^{205}Tl with $^2P_{1/2}$ ground state, where 2nd order Stark shift => (weak) tensor polarizability.

Potentially could have induced moment contributions to spin motion – terrible experimental complication.

Simple non-relativistic model

Assume CP violating interaction : $H_{CPV,N} = -a\vec{S}\cdot\vec{\mathcal{D}},$ $a < 10^{-11}\ \mathrm{fm}^{-2}$

in presence of which $|N\uparrow\rangle = \left(1 + a\mathcal{V}\vec{\mathcal{D}}\cdot\vec{S}\right)|\uparrow\rangle$ $\mathcal{V} = \sum_{n\neq\uparrow}\frac{|n\rangle\langle n|}{\omega_n}$

Realization of CP violating component of n $\eta|(t)\uparrow\rangle = a\mathcal{V}\vec{\mathcal{D}}\cdot\vec{S}|\uparrow\rangle.$

=> $a \sim 7\eta\ \mathrm{fm}^{-2}$

Electric dipole moment:

$$\begin{aligned}\langle\vec{d}_n\rangle &= ae\langle\uparrow|\vec{\mathcal{D}}\mathcal{V}\vec{\mathcal{D}}\cdot\vec{S}|\uparrow\rangle + c.c. \\ &= \frac{ae}{3\omega_{1/2}}\langle\vec{\mathcal{D}}^2\rangle\hat{z}\end{aligned}$$

Approximate relation of nEDM to electrical polarizibility

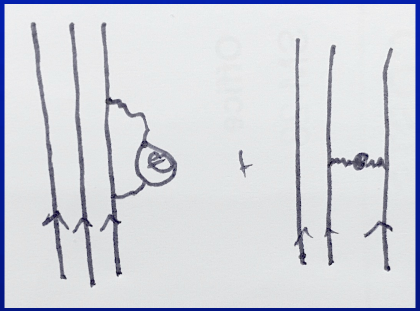
$$\frac{d_n}{\chi_n} = \frac{3a}{2e}\frac{1}{1+2\omega_{1/2}/\omega_{3/2}} \simeq \frac{a}{2e}$$

Understanding nEDM in bag models

Would like to see how CP violation of n states comes about in presence of QCD Θ interaction:

$$L_\theta = \theta \frac{g^2}{32\pi^2} \int d^3x F_a^{\mu\nu}(x) \tilde{F}^a_{\mu\nu}(x);$$

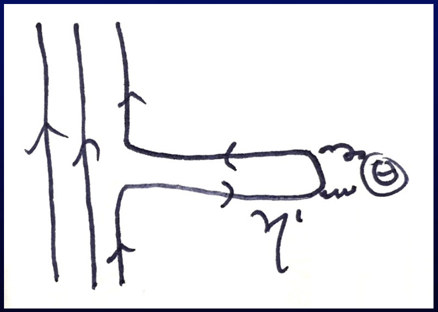
Direct implementation in bag models of n beset by gauge invariance non-trivialities.



Lattice QCD not yet successful.

Possible implementation in cloudy bag model: η' mesons in cloud. The η' massive through θ term. In cloudy bag θ term acting on η' in cloud can generate spontaneous n EDM.

S. Aoki &T. Hatsuda, PR D (1992)

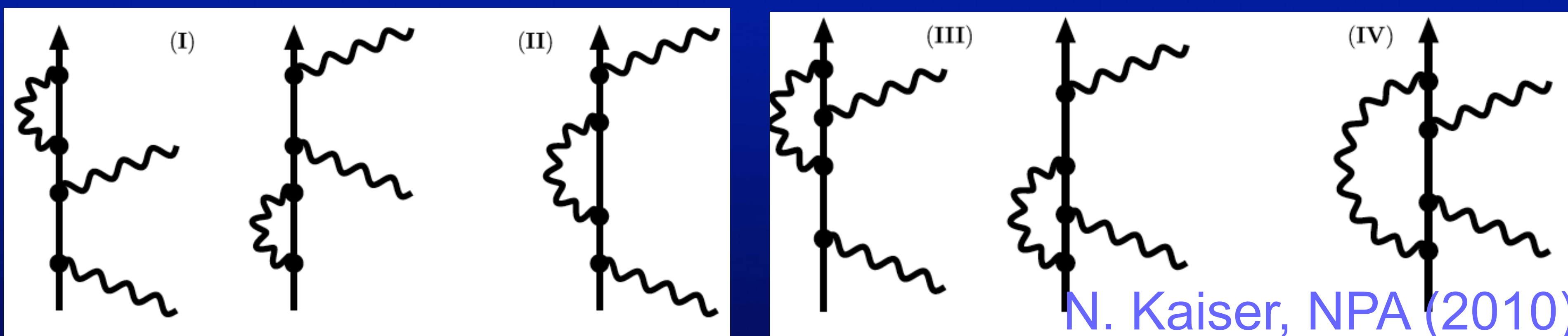


Related problems

Extend present picture to proton and electron in atoms.

Compute electric polarizability of electron -- via e^+e^- pairs in screening cloud?

For proton, extract polarizability in Compton scattering including radiative corrections.



N. Kaiser, NPA (2010)

Leads, for forward scattering, to multiplicative factor on top of Klein-Nishina cross section

$$[1 + (\alpha/2\pi)(2\omega/m)^2(\tfrac{8}{3}\ln(2\omega/m) + 11/18) + \ldots]$$

Low energy expansion of RCS cross section in terms of polarizabilities

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Lab}} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Lab}}^{\text{Powell}} - \frac{e^2}{4\pi M_N}\left(\frac{\nu'}{\nu}\right)^2 \nu\,\nu' \left\{\frac{\alpha+\beta}{2}(1+\cos\theta_L)^2 + \frac{\alpha-\beta}{2}(1-\cos\theta_L)^2\right\} + \mathcal{O}(\nu^3)$$

➡ Polarizability term : quadratic in the photon energy

➡ Angular dependence : disentangle α and β

$$\theta_L = 0^o \quad : \quad d\sigma \sim \alpha+\beta$$

$$\theta_L = 180^o \quad : \quad d\sigma \sim \alpha-\beta$$

➡ Higher terms in photon energy : can be treated in a dispersion relation formalism (see later)

Thank you!!

to my (not-so) old friend and colleague
Peter

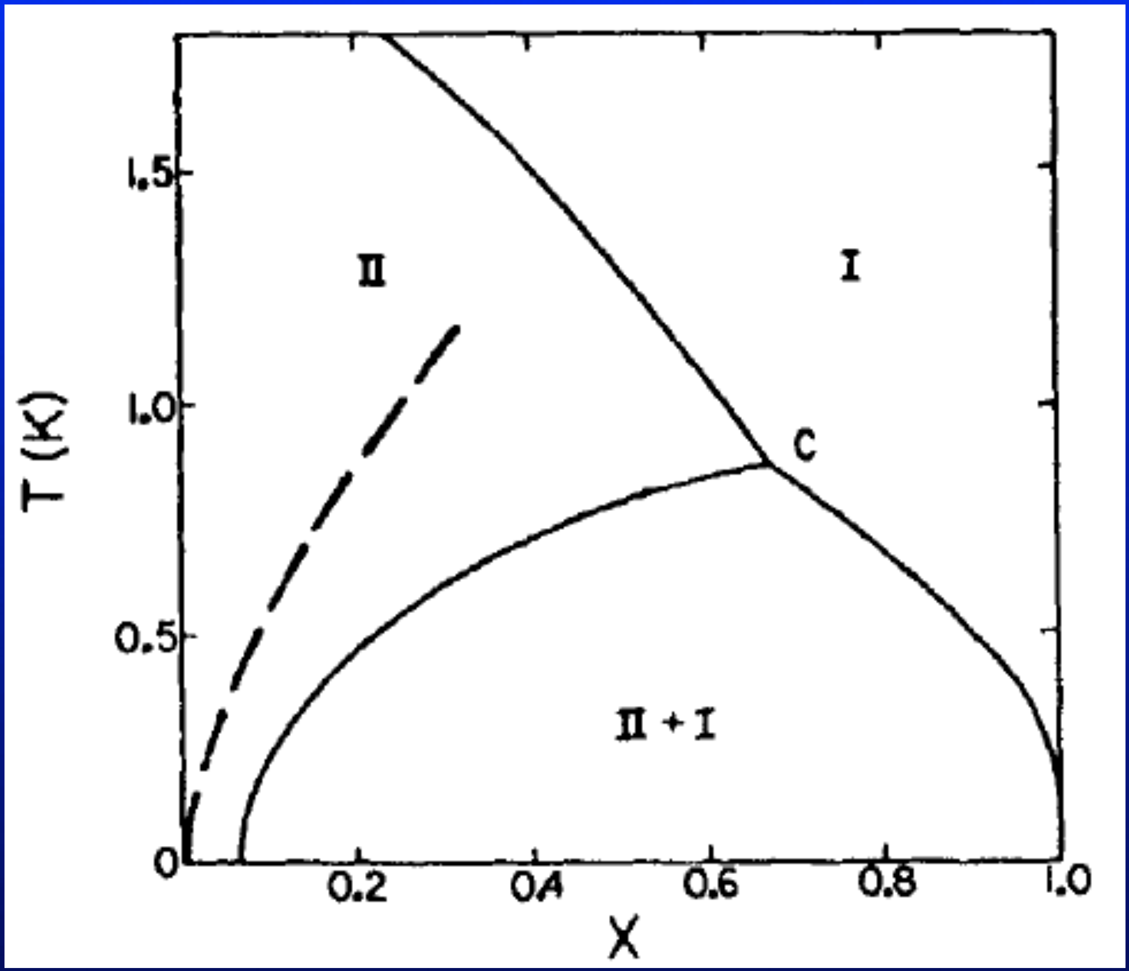
Sweeping depolarized ^{3}He out with phonon wind

- Use phonon – ^{3}He scattering
- Create phonons in superfluid with heater
  - phonon 'wind'

- Basic physics worked out long ago (~1960's)
  - ^{3}He concentration, x_3, in degenerate regime
  - now need processes at relative densities ~10^{-4}, 10^{-10} (natural: 10^{-7})

  - GB, D.H.Beck, C.Pethick, Phys. Rev. B **88** (2013) 014512, J. Low Temp. Phys. **178** (2015) 200, PR B 92, 024504 (2015)

Dilute solutions of ^{3}He in superfluid ^{4}He



Phase diagram
$x = n_3/n_{tot}$

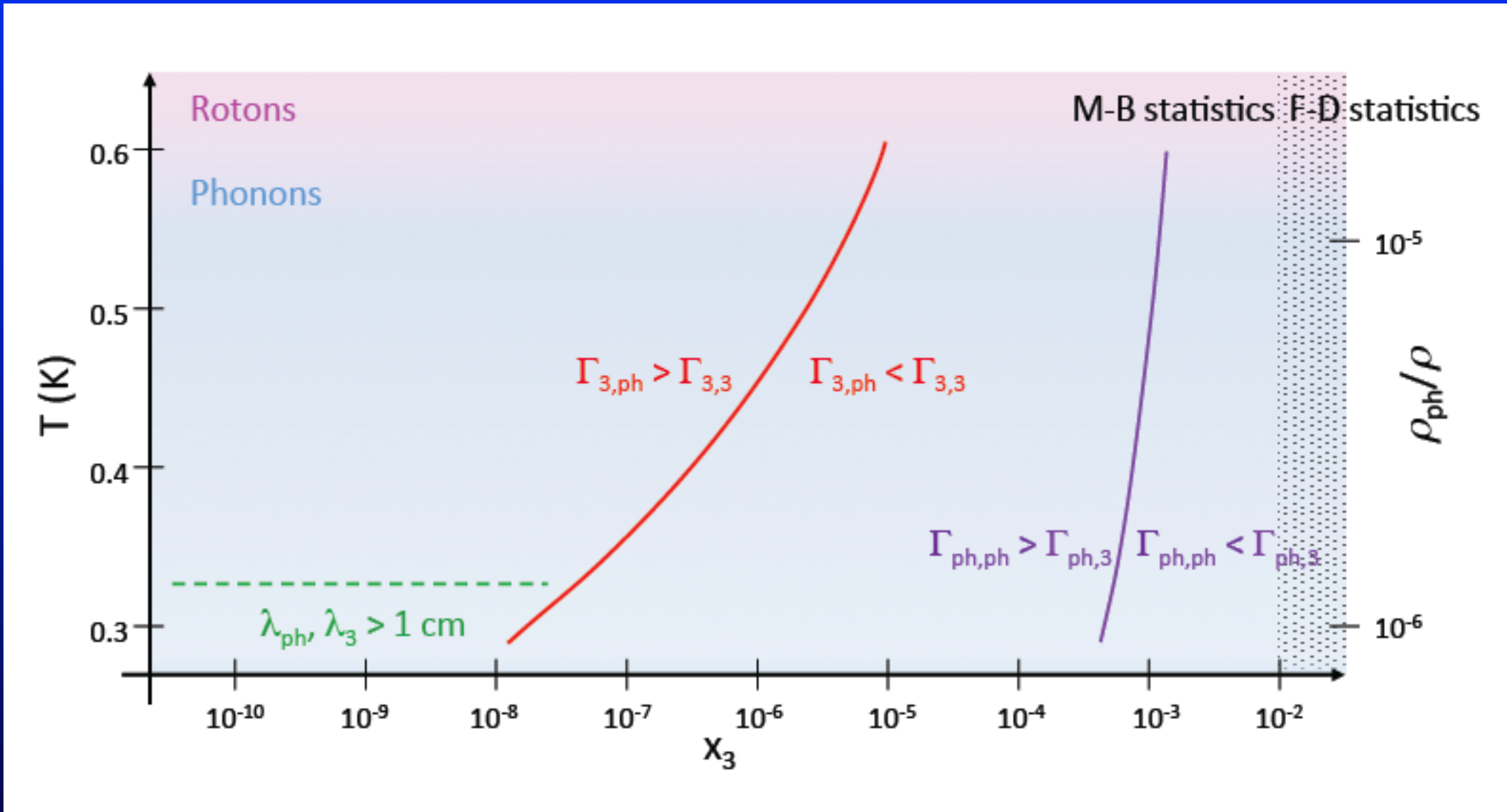
Degeneracy: D. Edwards 1965
Transport expts. J. Wheatley at el. 1966+
Microscopic theory, J. Bardeen, GB, D. Pines, C. Ebner, W. Saam
new superfluid?

Transport in solutions of ^3He in superfluid ^4He

- Goal is to determine dynamics of heat flush
  - Calculate thermal conductivities, diffusion coefficients
- Calculation based on
  - Phonon-^3He scattering cross section[1]
  - Phonon-phonon scattering mean free path[2]
  - ^3He-^3He scattering cross section[3]
  - Relaxation approximation for scattering from walls

1. C. Boghosian and H. Meyer, Phys. Lett. A **25** (1967) 352; B. M. Abraham, C. G. Brandt, Y. Eckstein, J. Munarin, and G. Baym, Phys. Rev. **188**, 309 (1969); G. E. Watson, J. D. Reppy and R. C. Richardson, Phys. Rev. **188** (1969) 384.
2. D. S. Greywall, Phys. Rev. B **23**, 2152 (1981); H. J. Maris, Rev. Mod. Phys. **49** (1977) 341.
3. A. C. Anderson, D. O. Edwards, R. Roach, R. J. Sarwinski and J. C. Wheatley, Phys. Rev. Lett. **17** (1966) 367; J. Bardeen, G. Baym and D. Pines, Phys. Rev. Lett. **17** (1966) 372, Phys. Rev. **156** (1967) 207; G. Baym and C. Ebner, Phys. Rev. **170** (1968) 346.

Relaxation rates: physics changes with ^{3}He concentration



GB, D.H.Beck, C.Pethick, Phys. Rev. B **88** (2013) 014512, J. Low Temp. Phys. **178** (2015) 200, PR B 92, 024504 (2015)

Time evolution of ^{3}He driven away by phonon wind

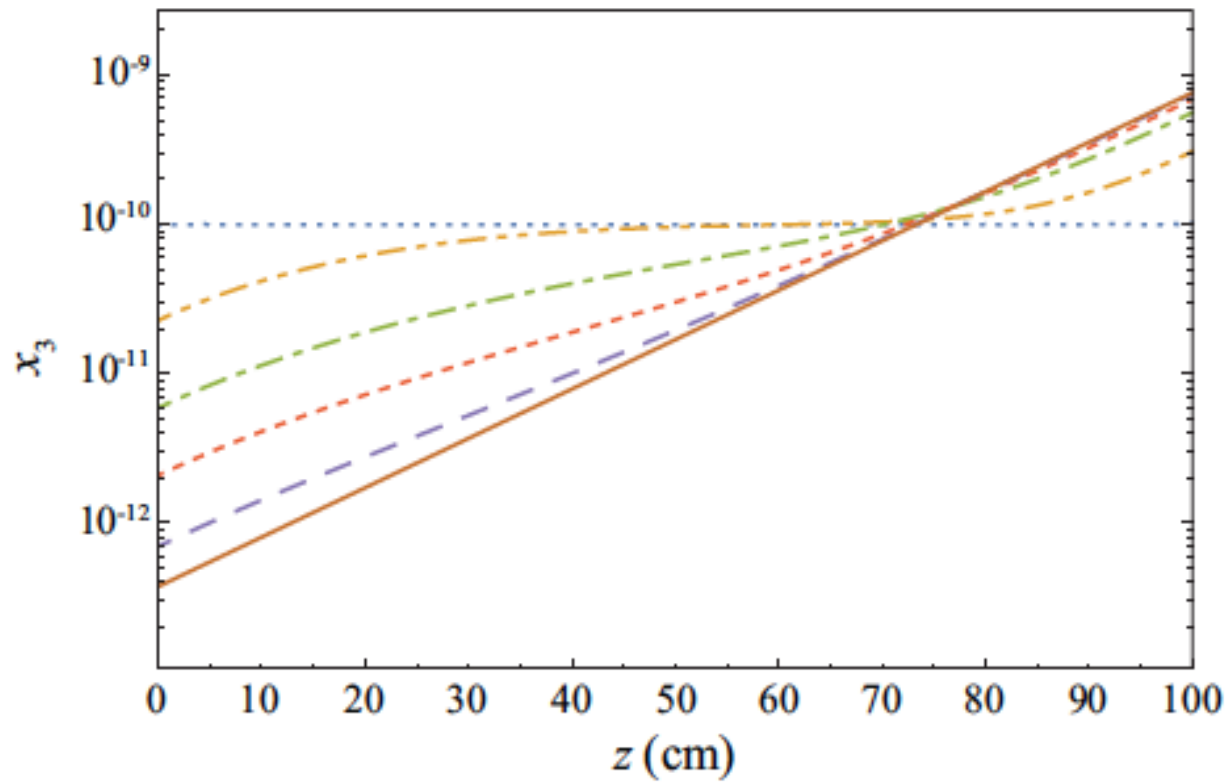


FIG. 3. (Color online) The ^{3}He concentration, x_3, from the solution of Eq. (39) as a function of z, the distance along the pipe, for various times: $t = 0$ (dotted), 1 (dash double dot), 3 (dash dot), 5 (short dash), 8 (long dash), and 20 s (solid). The result is shown for typical parameters in the nEDM experiment: $x_{3,0} = 10^{-10}$ and 5 mW of heat into a 3-cm-diameter, 100-cm-long pipe at a nominal temperature of 0.45 K.

GB, D.H.Beck, C.Pethick, PR B 92, 024504 (2015)

World-wide nEDM Searches

Experiment	UCN source	cell	Measurement techniques	σ_d Goal (10^{-28} e-cm)
ILL-PNPI	ILL turbine PNPI/Solid D_2	Vac.	Ramsey technique for ω E=0 cell for magnetometer	Phase1<100 < 10
ILL Crystal	Cold n Beam	solid	Crystal Diffraction Non-Centrosymmetric crystal	< 100
PSI EDM	Solid D_2	Vac.	Ramsey for ω, external Cs & ^{3}He, Hg co-magnetom. Xe or Hg comagnetometer	Phase1 ~ 50 Phase 2 < 5
Munich FRMII	Solid D_2	Vac.	Room Temp. , Hg Co-mag., also external Cs mag.	< 5
RCNP/TRIUMF	Superfluid ^{4}He	Vac.	Small vol., Xe co-mag. @ RCNP Then move to TRIUMF	< 50 < 5
SNS EDM	Superfluid ^{4}He	^{4}He	Cryo-HV, ^{3}He capture for ω, ^{3}He co-mag. with SQUIDS & dressed spins, supercond.	< 5
JPARC	Solid D_2	Vac.	Under Development	< 5
JPARC	Solid D_2	Solid	Crystal Diffraction Non-Centrosymmetric crystal	< 10?
LANL	Solid D_2	Vac.	R & D	~ 30

B. Filippone