Title: Foundations and Interpretation of Quantum Theory - Lecture 19

Date: Mar 25, 2010 02:30 PM

URL: http://pirsa.org/10030025

Abstract:

MESO/MACROSCOPIC TESTS OF QM: MOTIVATION

At microlevel: (a) $|\uparrow\rangle + |\downarrow\rangle$ quantum superposition ✓

$\neq$ (b) $|\uparrow\rangle$ OR $|\downarrow\rangle$ classical mixture ✗

how do we know? Interference

At macrolevel: (a) + quantum superposition

OR (b) OR macrorealism

✗ Decoherence DOES NOT reduce (a) to (b)!

Can we tell whether (a) or (b) is correct?

Yes, if and only if they give different experimental predictions. But if decoherence → no interference predictions of (a) and (b) identical.

⇒ must look for QIMDS

quantum interference of macroscopically distinct

What is "macroscopically distinct"?

(a) "extensive difference" Δ

(b) "disconnectivity" D

~large number of particles be differently in two branch

Initial aim of program: interpret raw

test (a) vs (b).

[illegible] "[illegible]" DECOHERENCE

("[illegible]" [illegible] ΔE [illegible] [illegible] $\gg \Delta E$ [illegible])

1. Matrix elements of S–E interaction [illegible] very [illegible] of [illegible] of S.

2. "Adiabatic" ("[illegible]") decoherence:

Ex.: spin-boson model

$$\hat{H} = \hat{H}_S + \hat{H}_E + \hat{H}_{S-E}$$

$$\hat{H}_S = \Delta \hat{\sigma}_x$$

$\hat{H}_E$ = set of SHO's, with lower frequency cutoff $\omega_{min} \gg \Delta$

$$\hat{H}_{S-E} = \hat{\sigma}_z \sum_\alpha C_\alpha \hat{x}_\alpha$$ [illegible]

$\Psi(t=0) = |+\rangle |\chi_0\rangle$ [illegible]

$\hat{\rho}_s(t=0) = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$ [illegible]

$\Downarrow$

$(t \sim \hbar/\omega_{min}) \cong \frac{1}{\sqrt{2}}(|+\rangle|\chi_+\rangle + |-\rangle|\chi_-\rangle)$

$\langle \chi_+ | \chi_- \rangle \sim \exp -$ [illegible]

$\hat{\rho}_s(t \sim \hbar/\omega_{min}) \cong \begin{pmatrix} \frac{1}{2} & 0 \\ 0 & \frac{1}{2} \end{pmatrix}$

("[illegible]" [illegible] ; $\Delta E \sim$ [illegible] $\exp -$ [illegible])

[illegible] $\gg \Delta E$ [illegible] decoherence)

1. Matrix elements of S-E interaction couple only a very restricted set of levels of S

2. "Adiabatic" ("[illegible]") decoherence:

Ex.: Spin-boson model

$$\hat H = \hat H_S + \hat H_E + \hat H_{S-E}$$

$$\hat H_S = \Delta \hat\sigma_z$$

$\hat H_E$ = sum of SHO's with lower frequency cutoff $\omega_{min} \gg \Delta$

$$\hat H_{S-E} = \hat\sigma_z \sum_\alpha C_\alpha \hat q_\alpha$$ [illegible]

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$[illegible](t \sim \hbar/\omega_{min}) \cong \frac{1}{\sqrt{2}}(|+\rangle|\chi_+\rangle + |-\rangle|\chi_-\rangle)$

$\langle\chi_+|\chi_-\rangle = \exp -F \cong 0$

$[illegible](t \sim \hbar/\omega_{min}) \cong \begin{pmatrix} \frac{1}{2} & 0 \\ 0 & \frac{1}{2} \end{pmatrix}$

1. Matrix elements of S-E interaction depend only on very restricted set of d.o.f. of E

2. "Adiabatic" ( ) decoherence

Ex.: spin-boson model

$$\hat{H} = \hat{H}_S + \hat{H}_E + \hat{H}_{S-E}$$

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$$\hat{H}_{S-E} = \hat{\sigma}_z \sum_\alpha C_\alpha \hat{q}_\alpha$$

$$\Psi_{SE}(t=0) = |+\rangle|\chi_0\rangle$$

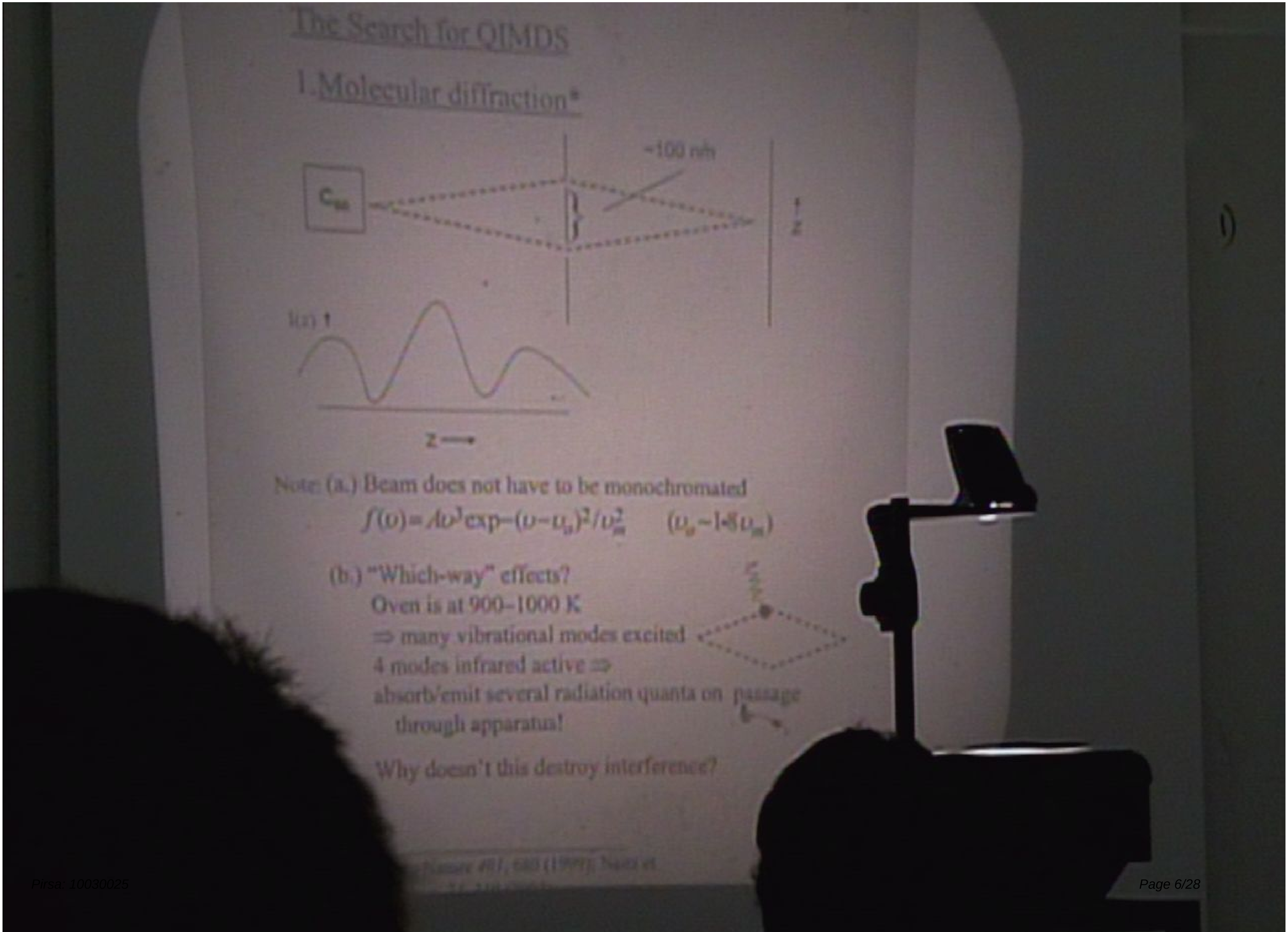
$$\hat{\rho}_S(t=0) = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

$$\Downarrow$$

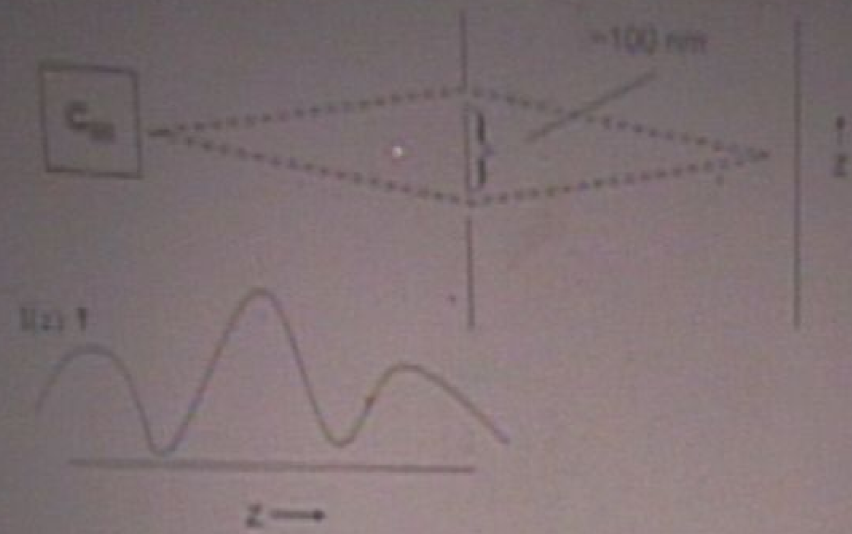
$$\Psi_{SE}(t \sim \hbar/\omega_{min}) \cong \frac{1}{\sqrt{2}}\left(|+\rangle|\chi_+\rangle + |-\rangle|\chi_-\rangle\right)$$

$$\langle \chi_+|\chi_-\rangle = \exp{-F} \cong 0$$

$$\hat{\rho}_S(t \sim \hbar/\omega_{min}) \cong \begin{pmatrix} \frac{1}{2} & 0 \\ 0 & \frac{1}{2} \end{pmatrix}$$


The Search for QIMDS
1. Molecular diffraction*
~100 nm
C_{60}
I(z)
z
Note: (a.) Beam does not have to be monochromated
$f(\upsilon) = A\upsilon^3 \exp -(\upsilon-\upsilon_0)^2/\upsilon_m^2 \qquad (\upsilon_0 \sim 1{\cdot}8\,\upsilon_m)$
(b.) "Which-way" effects?
Oven is at 900–1000 K
⇒ many vibrational modes excited
4 modes infrared active ⇒
absorb/emit several radiation quanta on passage
through apparatus!
Why doesn't this destroy interference?

... diffraction



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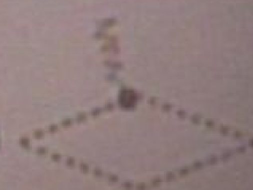
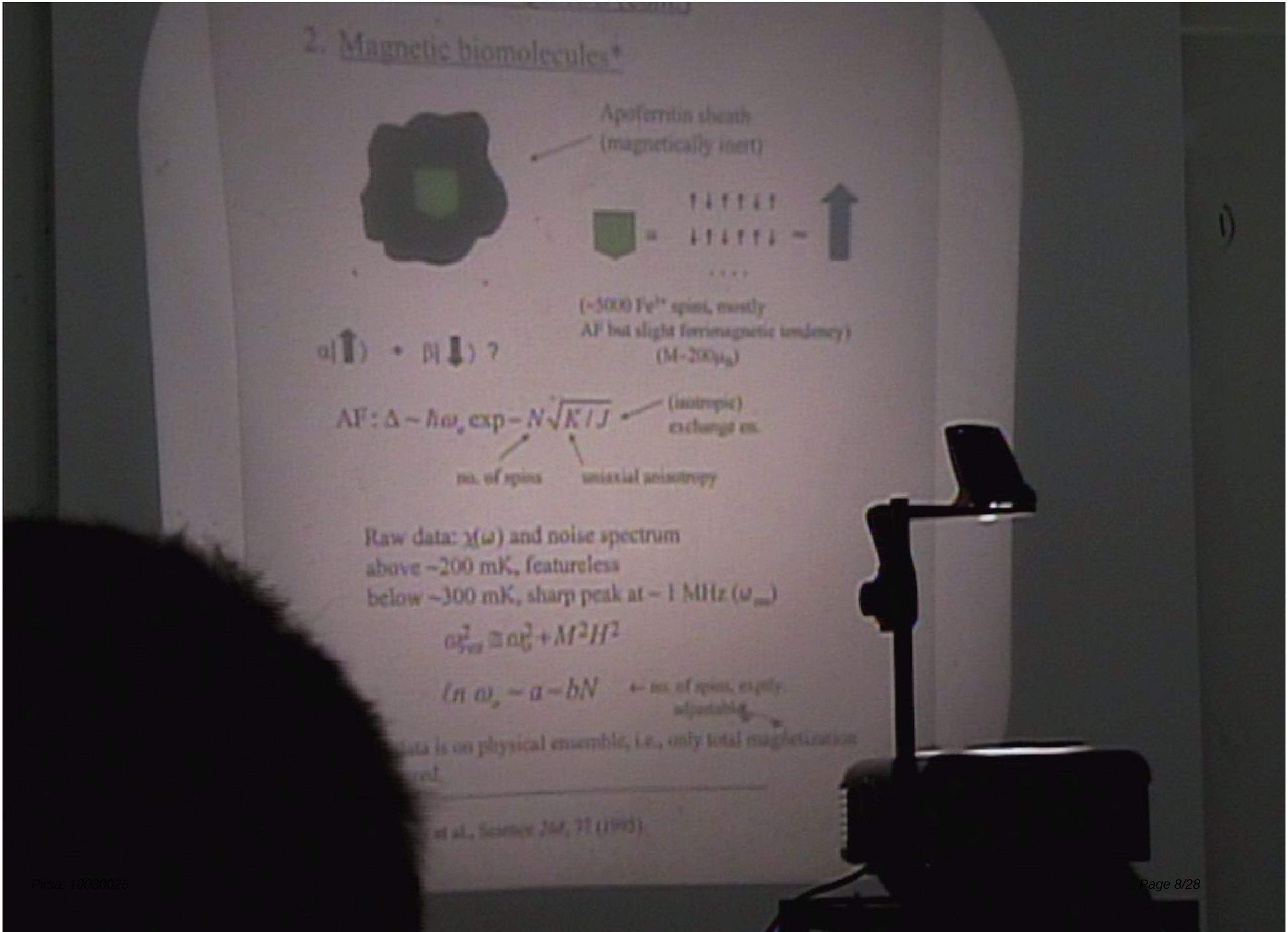


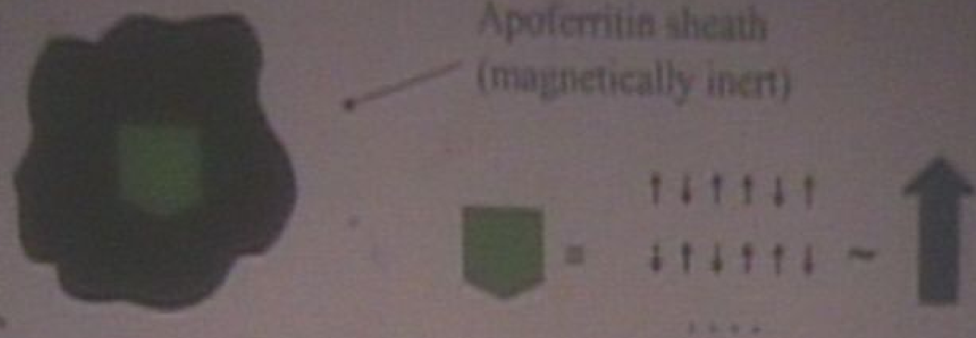
Why doesn't this destroy interference?

...ndt et al., Nature 401, 680 (1999); Nairz et ... , Am. J. Phys. 71, 319 (2003)


2. Magnetic biomolecules*
Apoferritin sheath
(magnetically inert)
(~5000 Fe^{3+} spins, mostly
AF but slight ferrimagnetic tendency)
($M \sim 200\mu_B$)
AF : $\Delta \sim \hbar\omega_e \exp - N\sqrt{K/J}$
(isotropic)
exchange en.
no. of spins
uniaxial anisotropy
Raw data: $\chi(\omega)$ and noise spectrum
above ~200 mK, featureless
below ~300 mK, sharp peak at ~ 1 MHz (ω_{res})
$\omega_{res}^2 \cong \omega_0^2 + M^2H^2$
$\ln \omega_e \sim a - bN$
← no. of spins, exptly.
adjustable
data is on physical ensemble, i.e., only total magnetization
et al., Science 268, 77 (1995).

The Search for QIMDS (cont.)

2. Magnetic biomolecules*



(~5000 Fe^{3+} spins, mostly AF but slight ferrimagnetic tendency)
($M \sim 200\mu_B$)

$\alpha|\Uparrow\rangle + \beta|\Downarrow\rangle$?

$$\mathrm{AF}: \Delta \sim \hbar\omega_o \exp - N\sqrt{K/J}$$

J: (isotropic) exchange en.

N: no. of spins

K: uniaxial anisotropy

Raw data: $\chi(\omega)$ and noise spectrum
above ~200 mK, featureless
below ~300 mK, sharp peak at ~ 1 MHz (ω_{res})

$$\omega_{res}^2 \cong \omega_0^2 + M^2H^2$$

$$\omega_o \sim a - bN$$

← no. of spins, exptly. adjustable

The Search for QIMDS (cont.)

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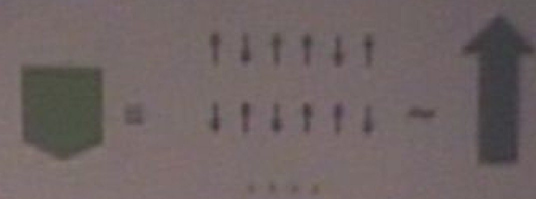
Apoferritin sheath
(magnetically inert)



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$$\omega_{res}^2 \cong \omega_0^2 + M^2H^2$$

$$\ln \omega_n \sim a - bN$$

← no. of spins, exptly. adjustable

The Search for QIMDS (cont.)

3. Quantum-optical systems*

$\sim 10^{12}$ Cs atoms

for each sample separately, and also for total

$$\left[J_x, J_y\right] = iJ_z$$

$$\Rightarrow \quad \left\langle \delta J_{x1} \delta J_{y1} \right\rangle \geq |J_{z1}|$$

$$\left\langle \delta J_{x2} \delta J_{y2} \right\rangle \geq |J_{z2}|$$

$$\left\langle \delta J_{x\,tot} \delta J_{y\,tot} \right\rangle \geq |J_{z\,tot}|$$

so, if set up a situation s.t.

$$J_{z1} = -J_{z2}$$

must have

$$\left\langle \delta J_{x1} \delta J_{y1} \right\rangle > 0$$

$$\left\langle \delta J_{x2} \delta J_{y2} \right\rangle > 0$$

but may have

Interpretation of idealized expt. of this type:

(QM theory $\Rightarrow$) $\langle \delta J_{x1} \delta J_{y1} \rangle \gtrsim |J_{z1}| \sim N$

$\Rightarrow |\delta J_{x1}| \gtrsim N^{1/2}$

But,

(expt $\Rightarrow$) $\langle \delta J_{xtot} \delta J_{ytot} \rangle \cong 0$ (#)

$\Rightarrow |\delta J_{xtot}| \sim 0$

$\Rightarrow \delta J_{x1}$ exactly anticorrelated with δJ_{x2}

$\Rightarrow$state is either superposition or mixture of $|n,-n>$

but mixture will not give (#) ...

value of J_{x1} value of J_{x2}

$\Rightarrow$ state must be of form

$$\sum_n c_n |n,-n>$$

with appreciable weight for $n \lesssim N^{1/2}$. $\Rightarrow$ high disconnectivity

Note:

(a) QM used essentially in argument

(b) $D \sim N^{1/2}$ not $\sim N$.
(prob. generic to this kind of expt.)

The Search for QIMDS (cont.)

4. Superconducting devices

(!: not all devices which are of interest for quantum computing are of interest for QIMDS)

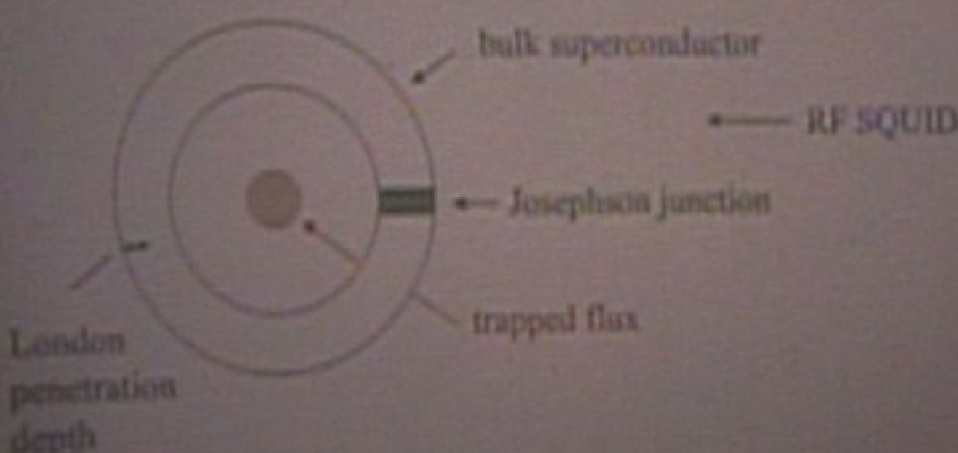
Advantages:

— classical dynamics of macrovariable v. well understood

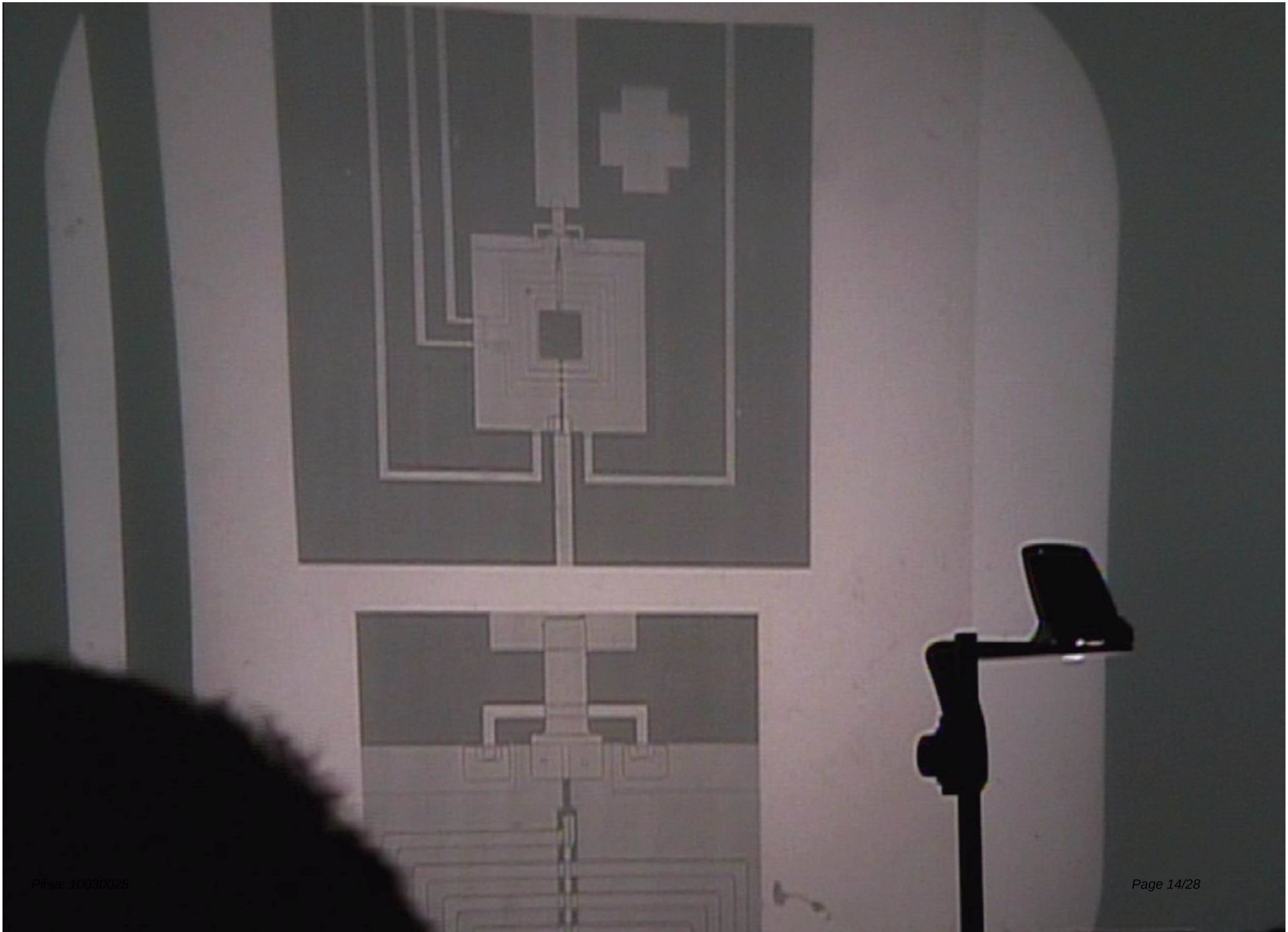
— intrinsic dissipation (can be made) v. low

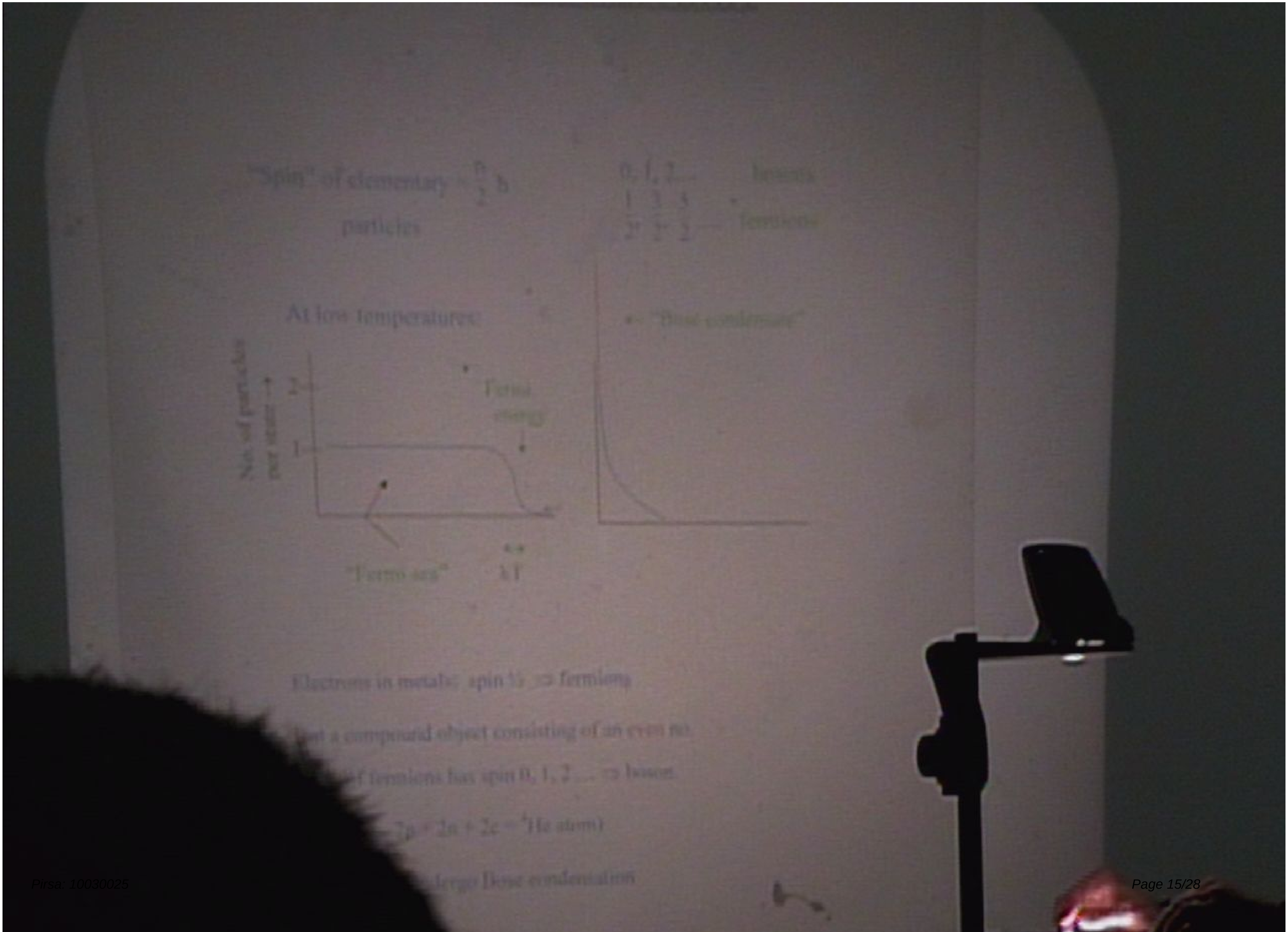
— well developed technology

— (non-) scaling of S (action) with D.



"Macroscopic variable" is trapped flux Φ



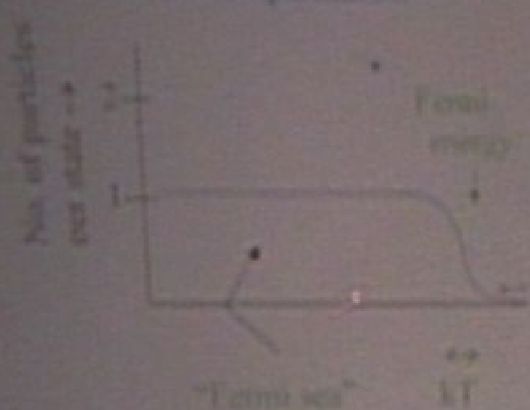

"Spin" of elementary particles
0, 1, 2 ... bosons
fermions
At low temperatures:
"Bose condensate"
No. of particles per state
Fermi energy
"Fermi sea"
kT
Electrons in metals: spin ½ => fermions
But a compound object consisting of an even no.
of fermions has spin 0, 1, 2 ... => boson
Bose condensation

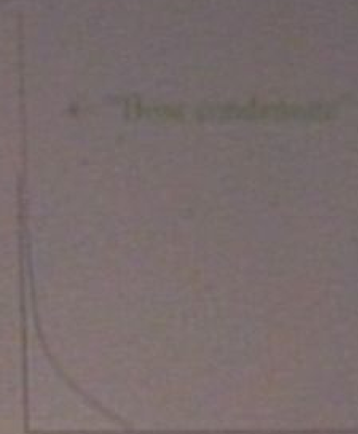
"Spin" of elementary $= \frac{n}{2}\,\hbar$
particles

$0, 1, 2, \ldots$ → bosons

$\frac{1}{2}, \frac{3}{2}, \frac{5}{2}, \ldots$ → fermions

At low temperatures:





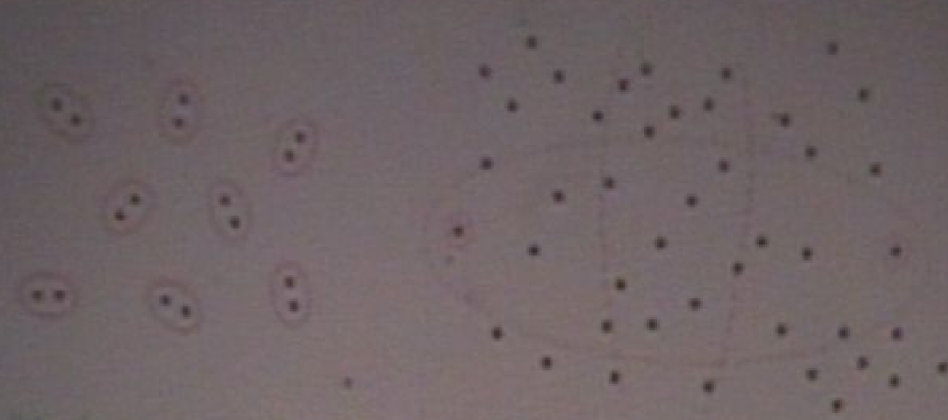
Electrons in metals: spin ½ ⇒ fermions

But a compound object consisting of an even no.
of fermions has spin 0, 1, 2 ... ⇒ boson.

(Ex: $2p + 2n + 2e = {}^4He$ atom)

can undergo Bose condensation

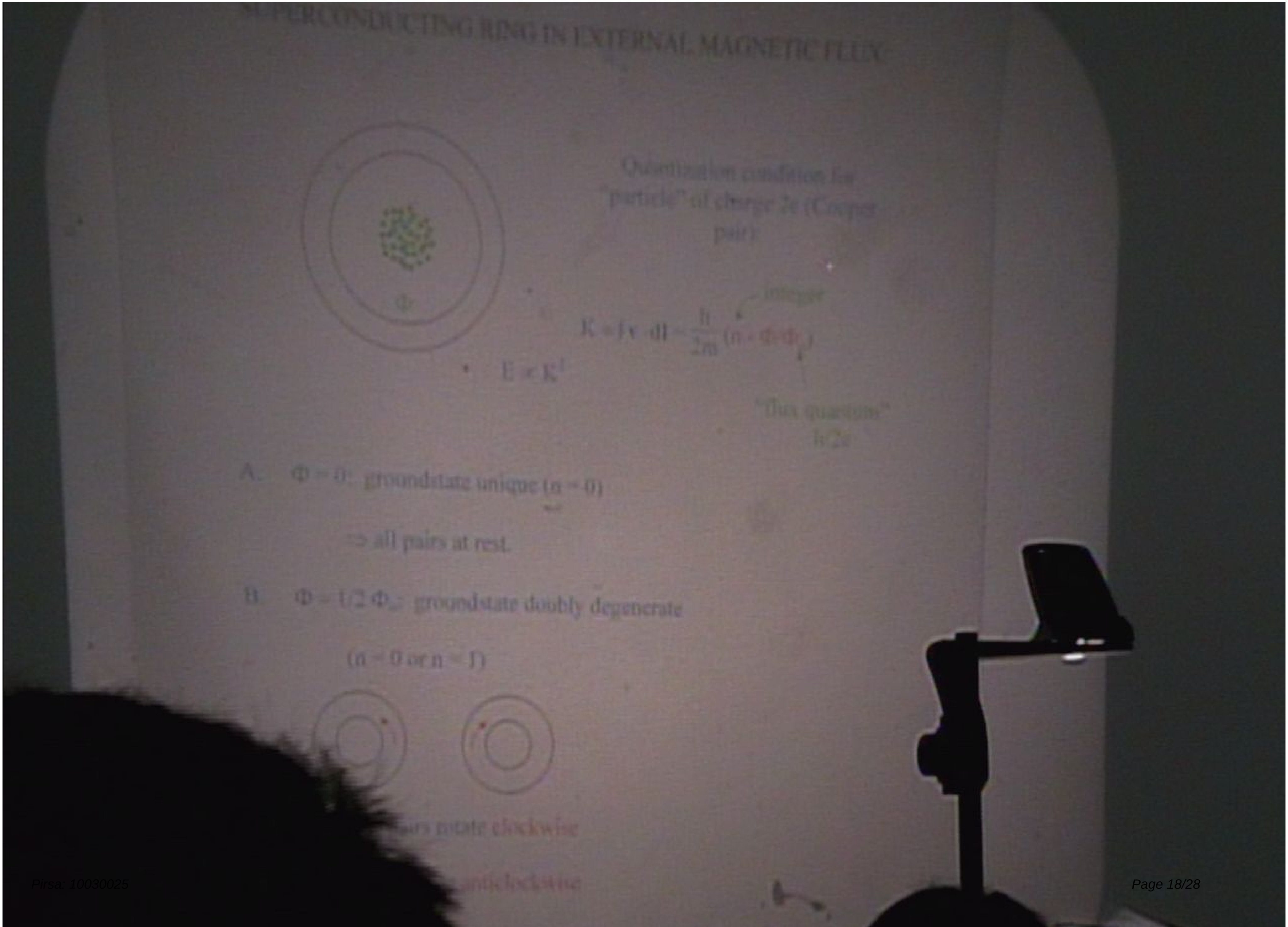
Pairing of electrons:



"di-electronic molecules"   Cooper Pairs

In simplest ("BCS") theory, Cooper pairs, once formed, must automatically undergo Bose condensation!

⇒ must all do exactly the same thing at the same time (also in nonequilibrium situation)


SUPERCONDUCTING RING IN EXTERNAL MAGNETIC FLUX:
Quantization condition for "particle" of charge 2e (Cooper pair):
integer
E ∝ K²
"flux quantum"
h/2e
A. Φ = 0: groundstate unique (n = 0)
⇒ all pairs at rest.
B. Φ = 1/2 Φ₀: groundstate doubly degenerate
(n = 0 or n = 1)
rotate clockwise
anticlockwise

SUPERCONDUCTING RING IN EXTERNAL MAGNETIC FLUX

Quantisation condition for "particle" of charge 2e (Cooper pair)

integer

$$K = \oint \mathbf{v} \cdot d\mathbf{l} = \frac{h}{2m}(n - \Phi/\Phi_o)$$

"flux quantum" h/2e

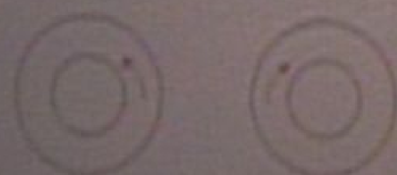
- $E \propto K^2$

A. $\Phi = 0$: groundstate unique ($n = 0$)

$\Rightarrow$ all pairs at rest.

B. $\Phi = 1/2\, \Phi_o$: groundstate doubly degenerate

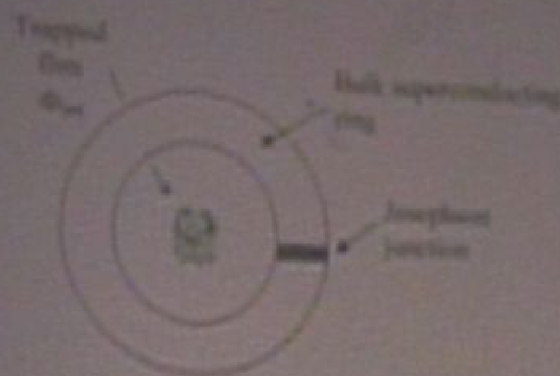
($n = 0$ or $n = 1$)

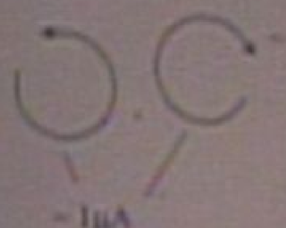


Either all pairs rotate clockwise

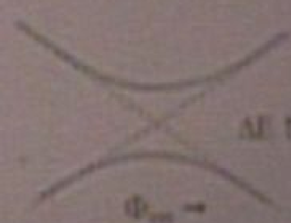
Or all pairs rotate anticlockwise

Josephson circuits





$\Psi = 2^{-1/2}\,(|↺\rangle + |↻\rangle)$



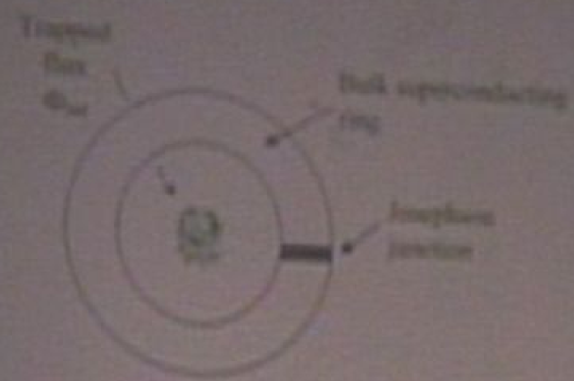
Evidence: (a) spectroscopic
(SUNY, Delft 2000)

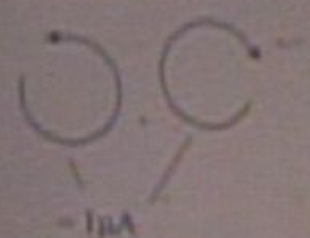
(b) real-time oscillations (like NH_3)

between ↺ and ↻

2002, Delft 2003) (Q ~ 10-150)

Josephson circuits





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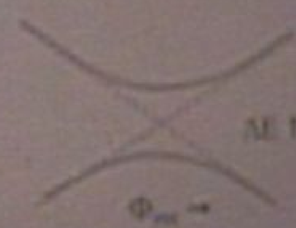

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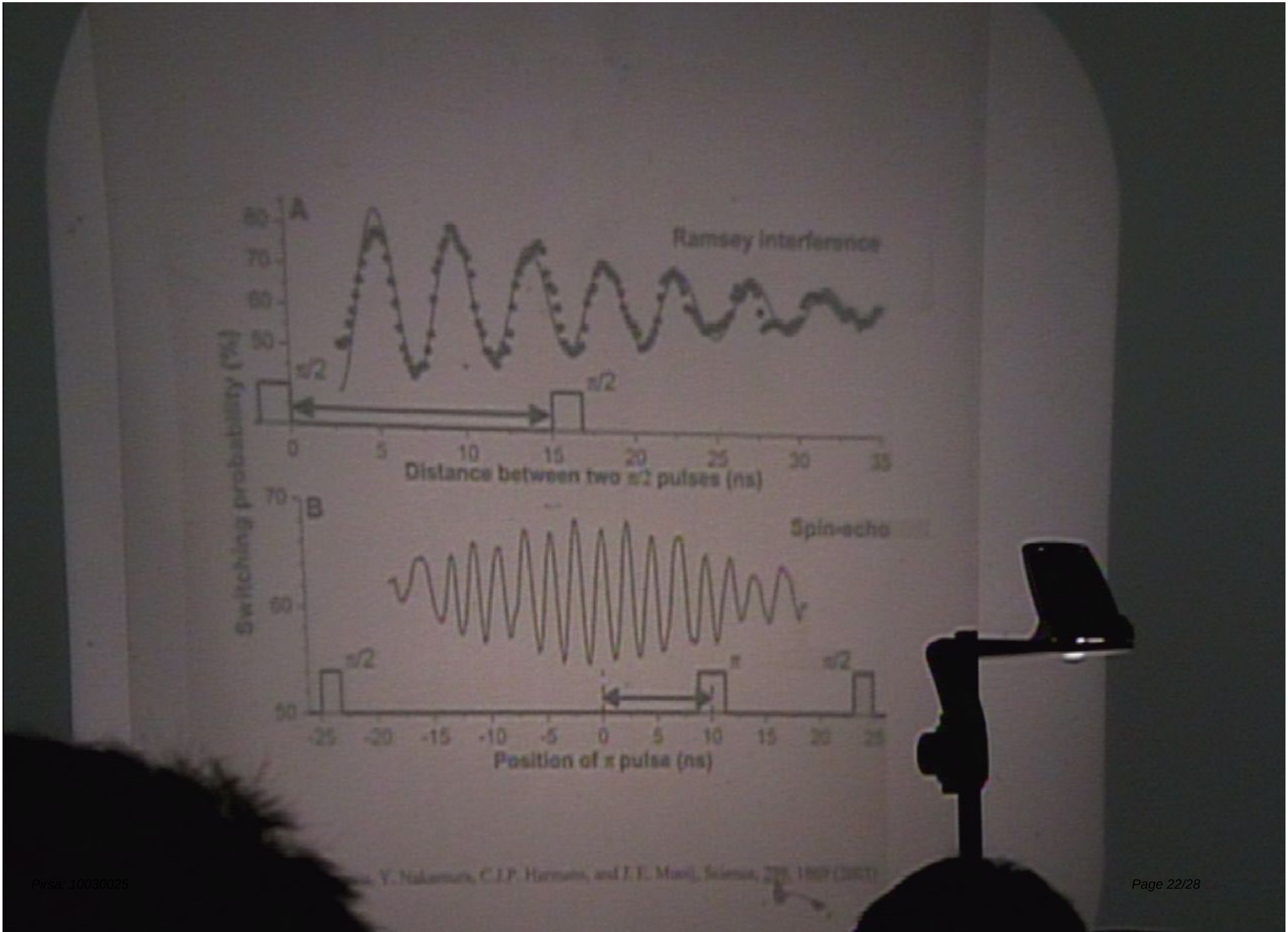
A
Ramsey interference
Switching probability (%)
Distance between two π/2 pulses (ns)
π/2
B
Spin-echo
Position of π pulse (ns)
π
Y. Nakamura, C.J.P. Harmans, and J.E. Mooij, Science

IS THE DISCONNECTIVITY "D" ("SCHRÖDINGER'S-CATTINESS")
OF THE STATES OBSERVED IN QIMDS EXPERIMENTS?

i.e., how many "microscopic" entities are "behaving differently" in the two branches of the superposition?

Fullerene (etc.) diffraction experiments: straightforward, number of "elementary" particles in C_{60} (etc.) (~1200)

Magnetic biomolecules: number of spins which reverse between the two branches (~5000)

Quantum-optical experiments
SQUIDS
} matter of definition

e.g. SQUIDS (SUNY experiment):

(a) naive approach:

no. of C. pairs

$$\Psi_{\curvearrowleft} \sim \chi_{\curvearrowleft}^{N/2}, \quad \Psi_{\circlearrowright} = \chi_{\circlearrowright}^{N/2}$$

mutually orthogonal C. pair w.f.

$\Rightarrow D \sim N \sim 10^9 - 10^{10}$ ↯ Fermi statistics!

(b) how many single electrons do we need to displace in momentum space to get from $\Psi_{\curvearrowleft}$ to $\Psi_{\circlearrowright}$? (Korsbakken et al., preprint, Nov. 08)

$\Rightarrow D \sim N(v_s/v_F) \sim 10^3 - 10^4$ ↯ intuitively, severe underestimate in "BEC" limit (e.g. Fermi alkali gas)

WHAT IS THE DISCONNECTIVITY "D" ("SCHRODINGER'S-CATTINESS") OF THE STATES OBSERVED IN QIMDS EXPERIMENTS?

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...) $\sim 10^3 - 10^4$ ☞ intuitively, severe underestimate in "BEC" limit (e.g. Fermi alkali gas)

	DIFFERENCE	ENTANGLEMENT
Single e	1	1
Neutron in interferometer	$\sim 10^{3}$	1
QED cavity	~ 10	$\lesssim 10$
Cooper-pair box	$\sim 10^{3}$	2
C_{60}	~ 1100	~ 1100
Ferritin	~ 5000 (?)	~ 5000
Aarhus quantum-optics expt.	$\sim 10^{[illegible]}$ ($\approx 10^{[illegible]}$)	$\sim 10^{[illegible]}$
SUNY SQUID expt.	$\sim 10^{[illegible]} - 10^{[illegible]}$ ($\approx$ [illegible])	($10^{[illegible]}$–$10^{[illegible]}$)
Smallest visible dust particle	$\sim 10^{[illegible]}$	($10^{[illegible]}$–$10^{[illegible]}$)
[illegible]	$\sim 10^{[illegible]}$	$\sim 10^{[illegible]}$

Where do we go from here?

1. Larger values of Λ and/or D?
   (Diffraction of virus?)

2. Alternative Dfs. of "Measures" of Interest

   — More sophisticated forms of entanglement?*
   — Biological functionality (e.g. superpose states of rhodopsin?)
   — Other (e.g. GR)

3. Exclude Macrorealism

Suppose: Whenever observed, $Q = \pm 1$.

$Q = +1$ $\quad$ $Q = -1$

Df. of "MACROREALISTIC" Theory:

I. $Q(t) = \pm 1$ at (almost) $\forall$ t,

   whether or not observed.

II. Noninvasive measurability

III. Induction

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Df. of "MACROREALISTIC" Theory:

"COMMON SENSE"?

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whether or not observed.

II. Noninvasive measurability

III. Induction

$$K(1,2,3,4) \equiv \langle Q(t_1)Q(t_2)\rangle_{\text{av}} + \langle Q(t_2)Q(t_3)\rangle_{\text{av}} + \langle Q(t_3)Q(t_4)\rangle_{\text{av}} - \langle Q(t_1)Q(t_4)\rangle_{\text{av}}$$

Take $t_2 - t_1 = t_3 - t_2 = t_4 - t_3 = \pi/4\Delta$ ← tunnelling frequency

Then,

(a) Any macrorealistic theory: $K \leq 2$

(b) Quantum mechanics, ideal: $K = 2.8$

(c) Quantum mechanics, with all the real-life complications: $K > 2$ (but < 2.8)

Thus: to extent analysis of (c) within quantum mechanics is reliable, can force nature to choose between macrorealism and quantum mechanics!

Possible outcomes:

...gh noise $\Rightarrow K_{QM} < 2$

...realism refuted