nEDM at KEK-RCNP

the first step to nEDM at TRIUMF

Y. Masuda (KEK)

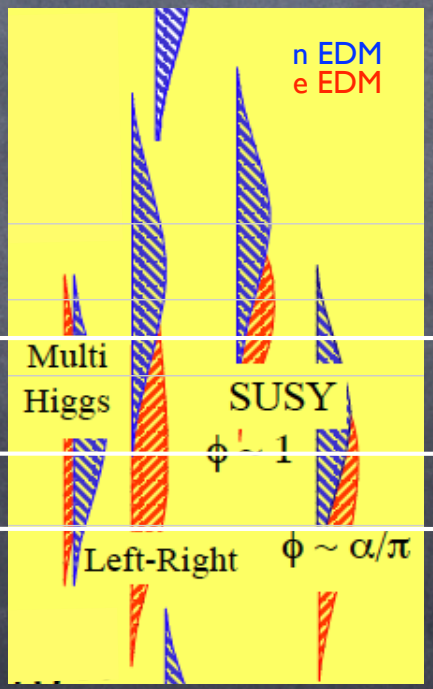
New physics predicts EDM

Earth's field ($\mu_n H_0/E$) →

EDM upper limit →

statistical 1.5×10^{-26}
systematic 0.7×10^{-26}
related with B

10^{-16}
10^{-18}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
e.cm



Statistical
high density UCN

at RCNP
10^{-27} e.cm

at TRIUMF
10^{-28} e.cm

Systematic
new magnetometer
10^{-28} e.cm

Our approach to nEDM

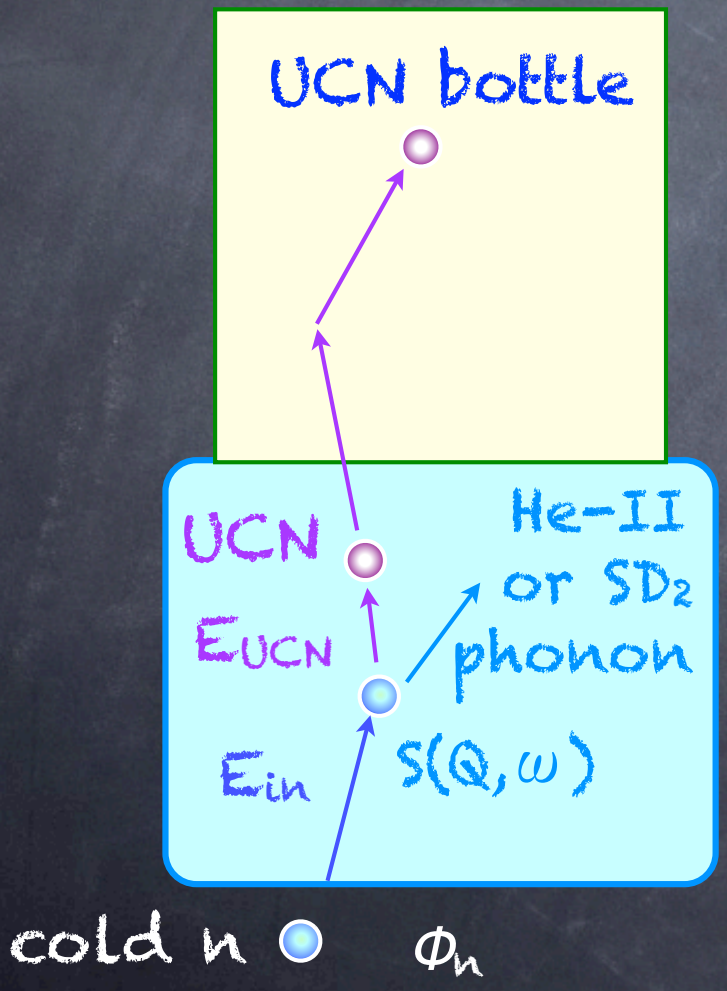
1 Spallation UCN production in He-II
for counting statistics

2 ^{129}Xe co-magnetometer
for systematic error

Super-thermal UCN source

Neutron cooling by using phonon phase space

ILL, KEK-RCNP, LANL, PSI, Munich, SNS, NCSU, Indiana, PNPI



P : production rate

$$\int\int dE_{in} dE_{UCN} \; N\sigma(E_{in} \rightarrow E_{UCN}) \, d\Phi_n(E_{in})/dE_{in}$$

$$d^2\sigma/dQd\omega = k_f/k_i \; \sigma_{coh}/4\pi \; S(Q,\omega)$$

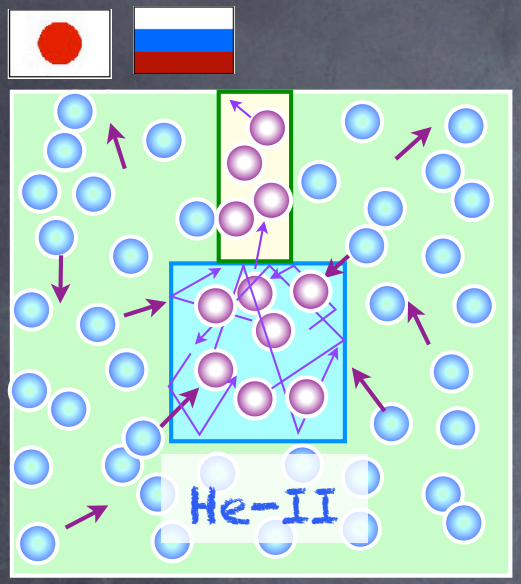
$$\rho_{UCN} = P\tau_s\{1-\exp(-t/\tau_s)\}$$

$$\rightarrow P\,t \quad t \ll \tau_s$$

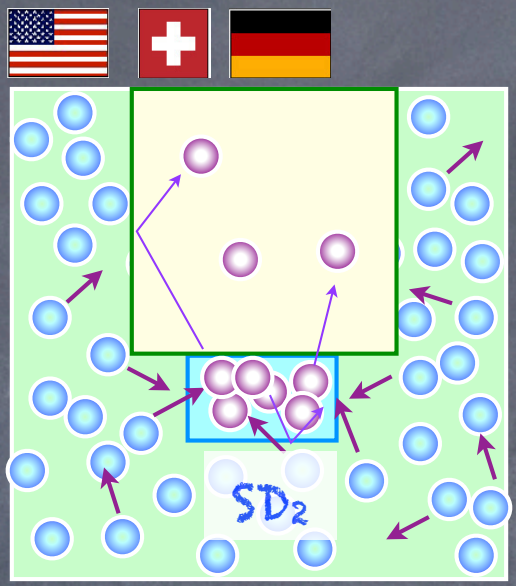
$$\rightarrow P\tau_s \quad t \gg \tau_s$$

τ_s : storage lifetime

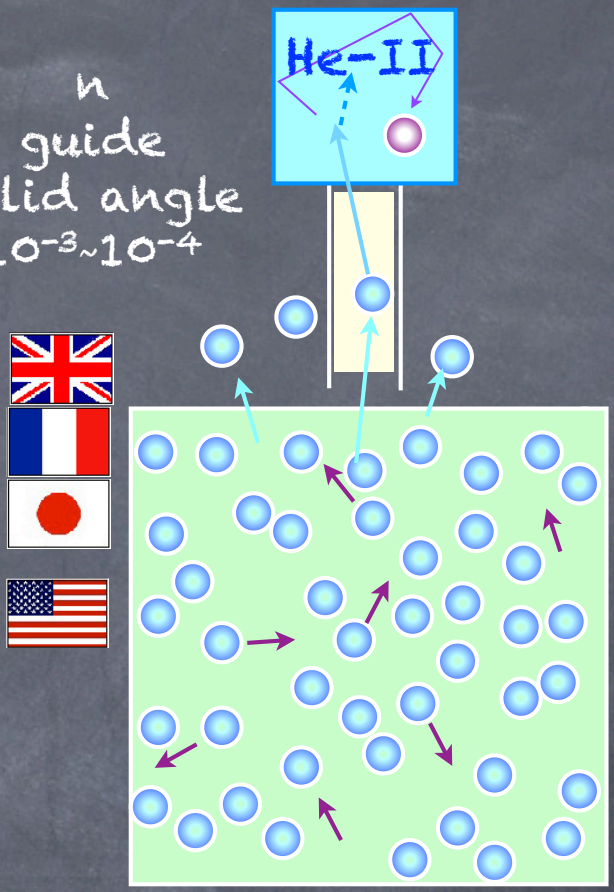
New UCN sources



Cold
n
source



n
guide
solid angle
10^{-3}~10^{-4}



ρ_{UCN} = P(production) $\times T_s$(life) $\times \varepsilon_{ext}$(extraction) $\times \varepsilon_d$(dilution)

P	midium	large	small
T_s	long	short	long
ε_{ext}	large	small	large
ε_d	large	small	large

Our approach to high density UCN

1 $\rho_{UCN} = P\tau_s$ (or $P\ t$)

Long period for UCN production:

We don't need high proton current.

Time constant of UCN EDM measurement is long.

2 Large volume for UCN production:

Very long UCN mean free path.

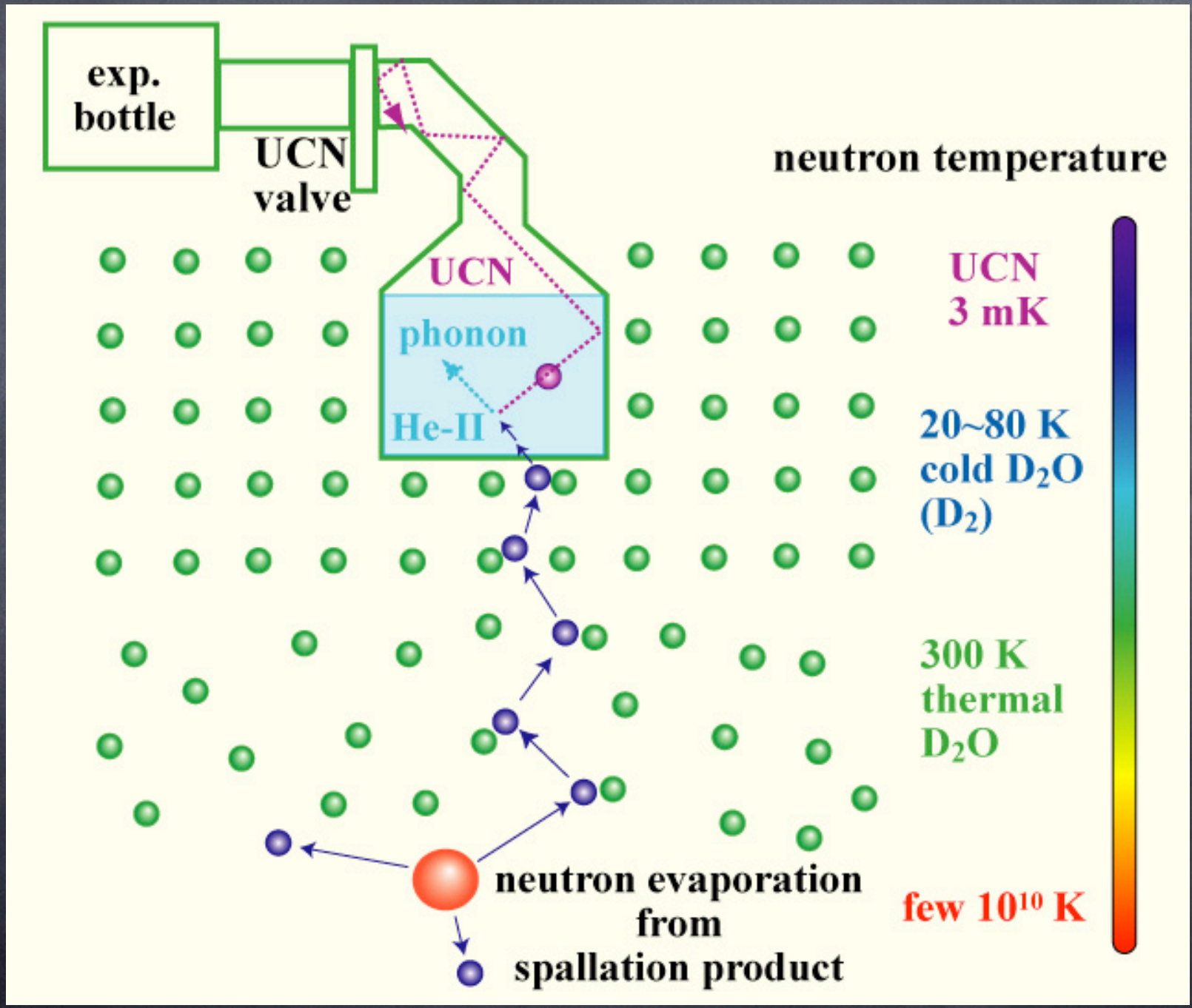
Dilution upon EDM cell filling is reduced.

3 Spallation:

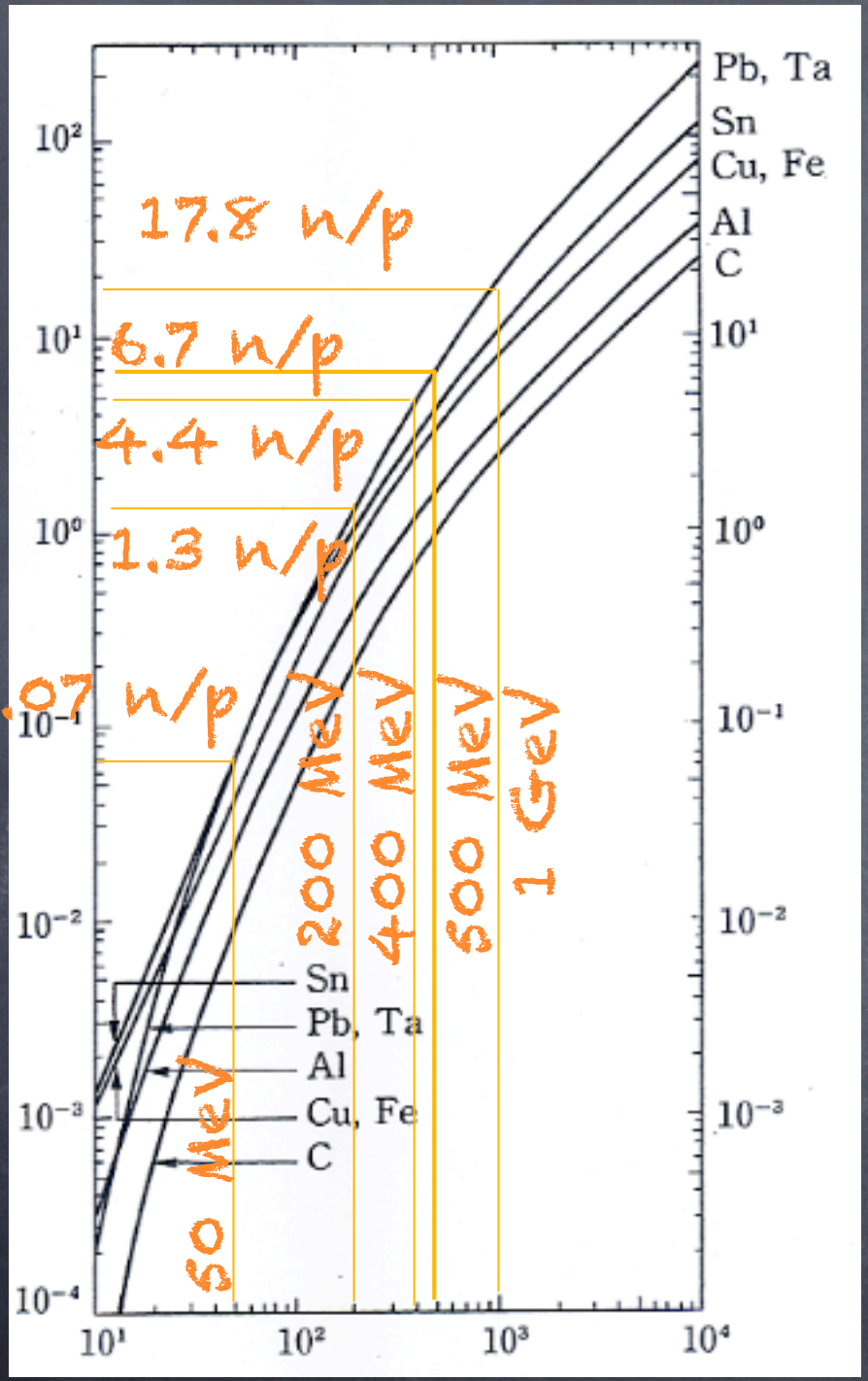
Background and gamma heating are cut off during measurement.

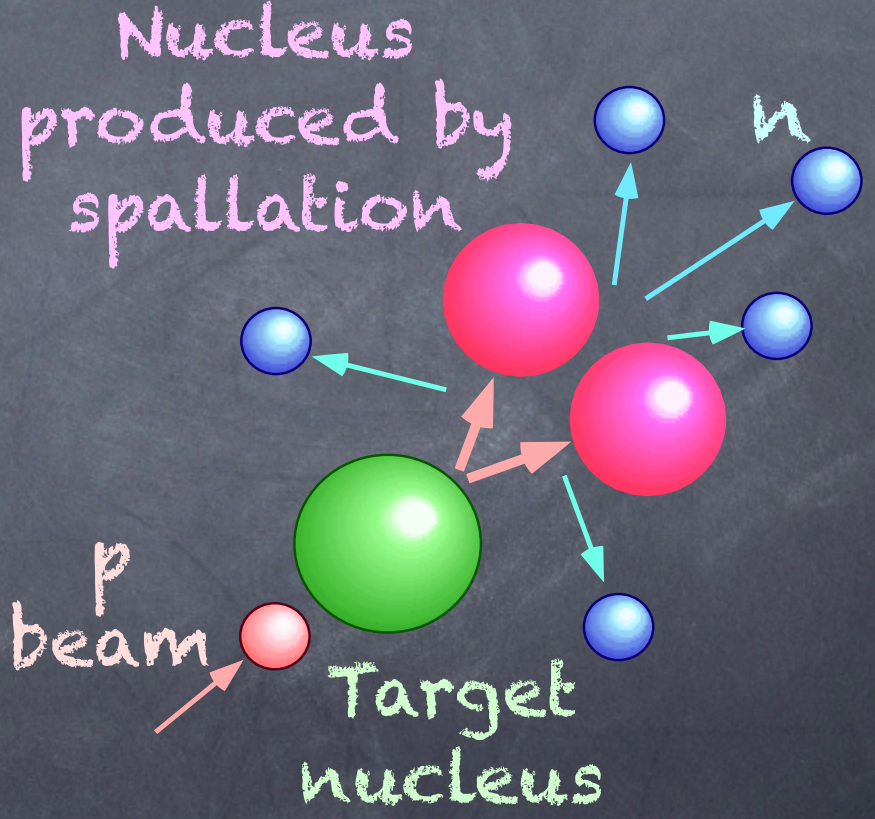
We use He-II and cyclotron

Our UCN production



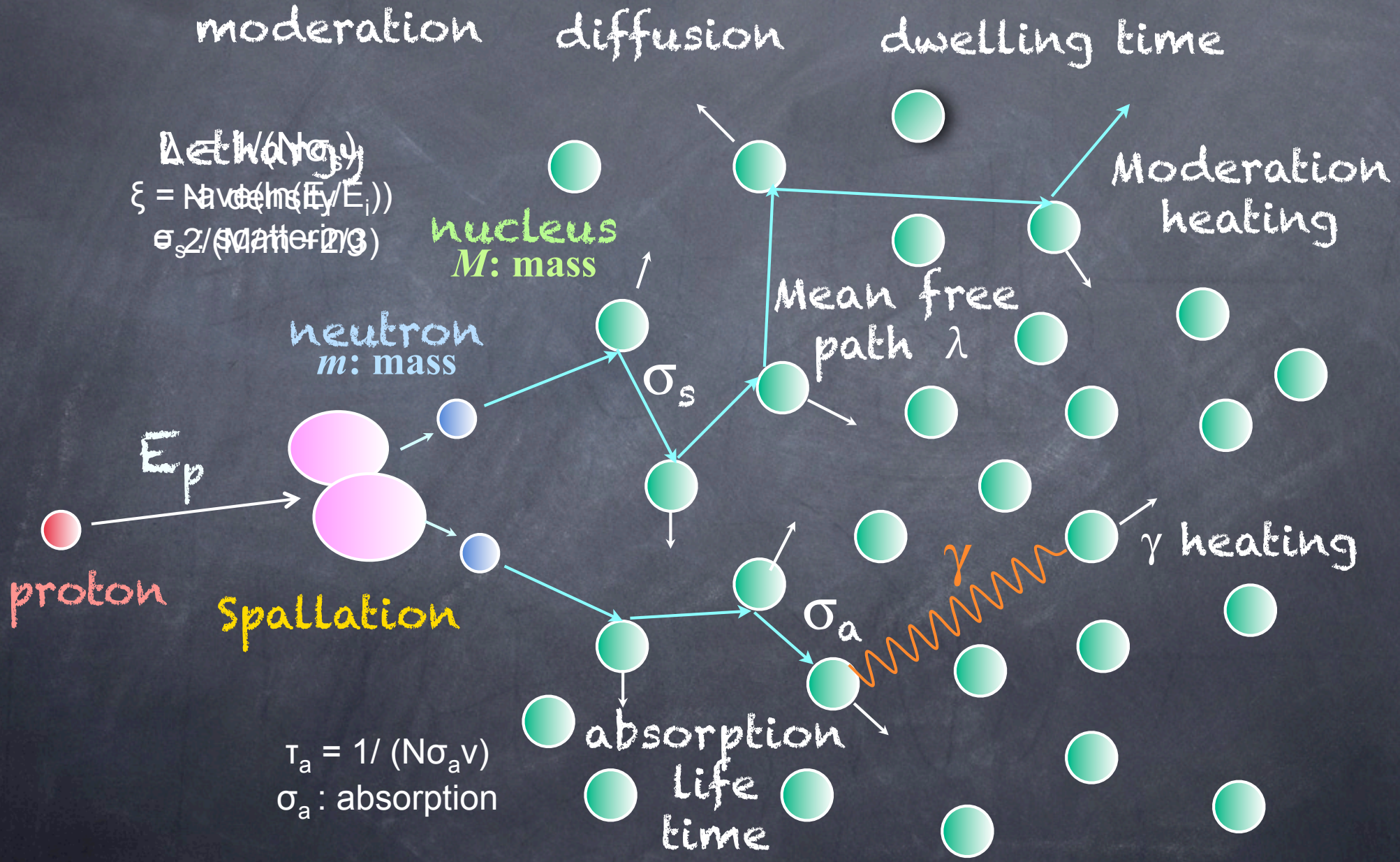
Spallation n production





K. Tesch (1985)

Neutron source parameters

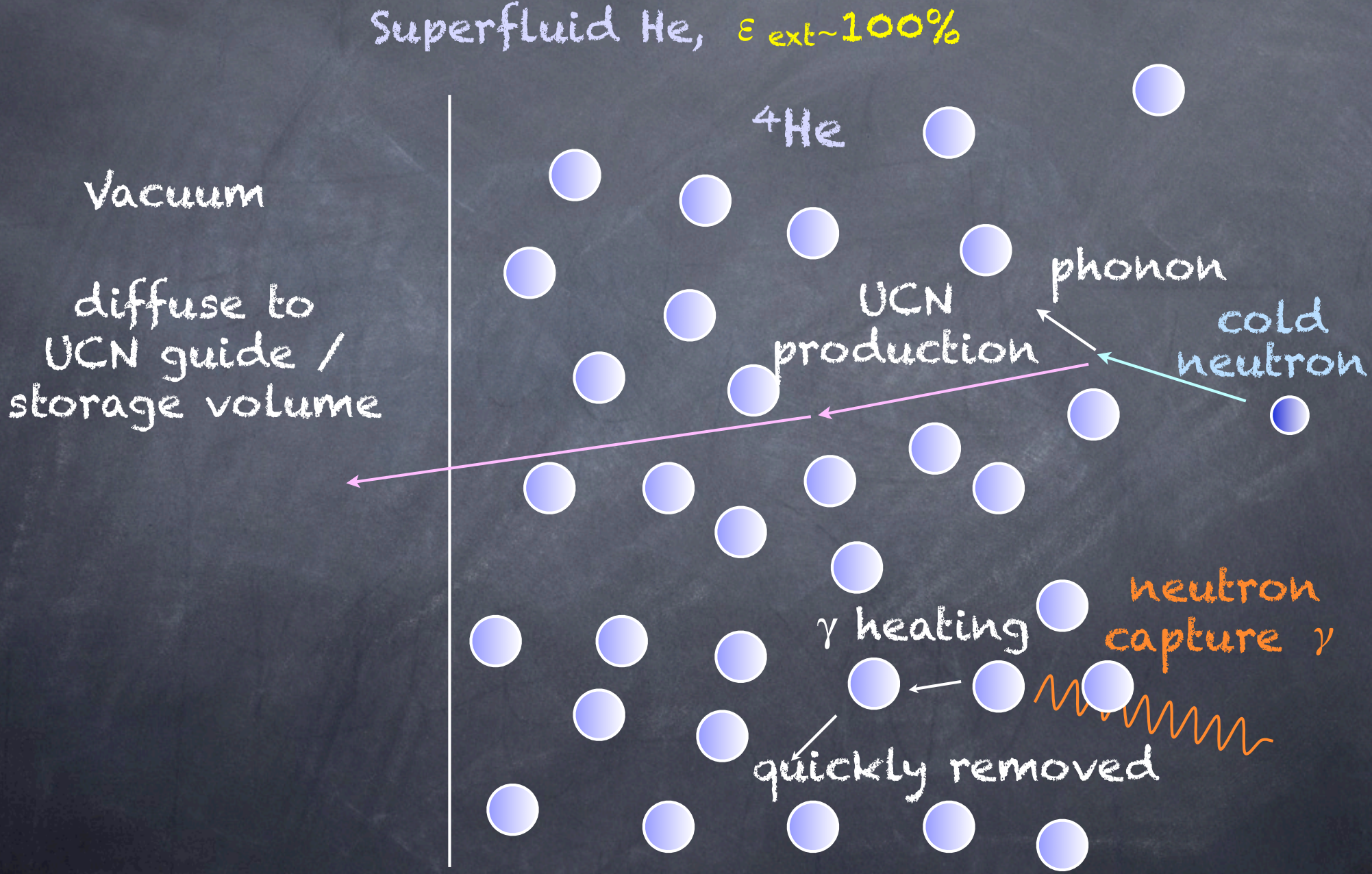


Moderator material

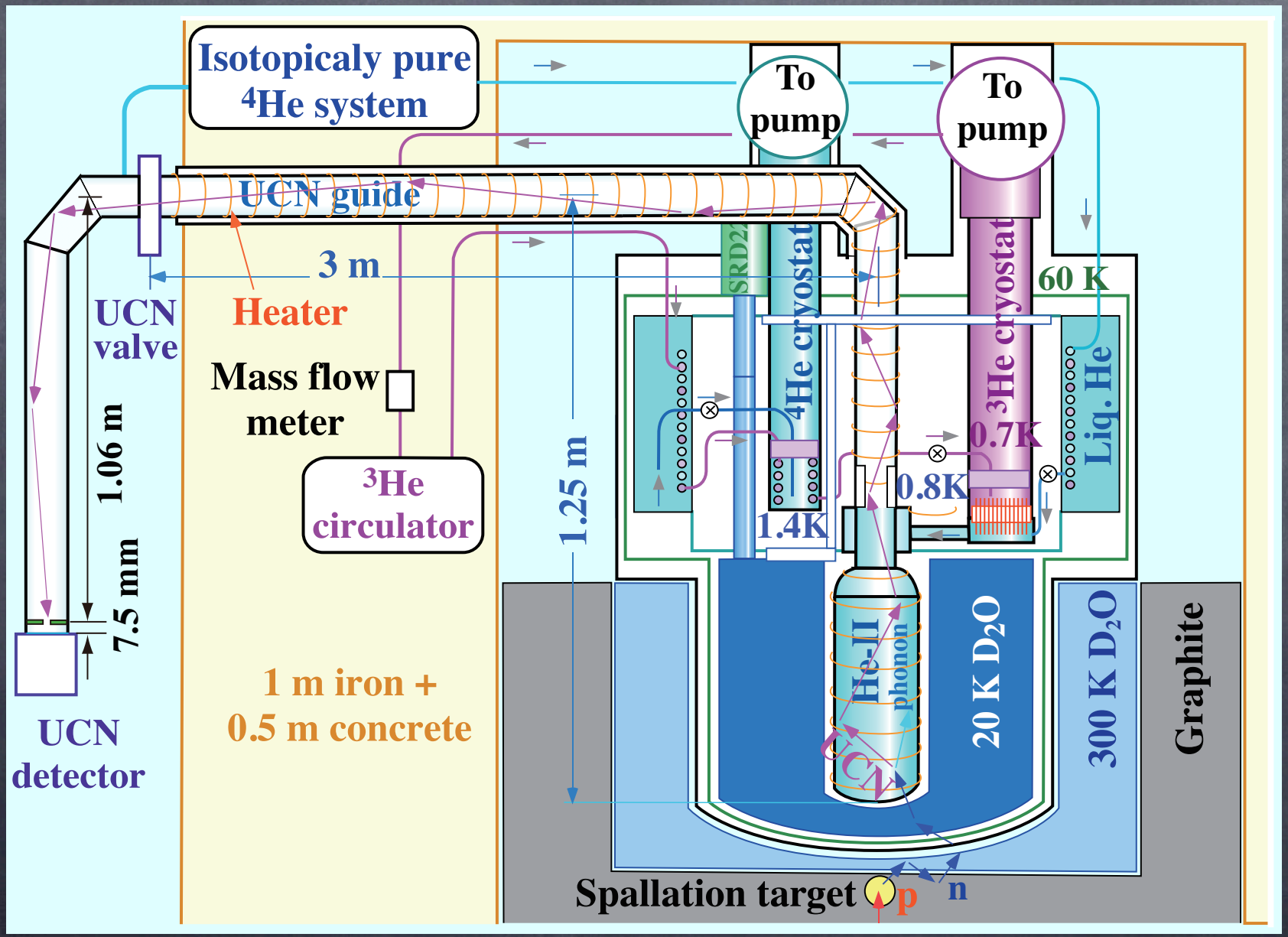
For high Φ_n at 1 meV, high lethargy
short mean free path, low absorption (= low γ heating)

	H_2O	D_2O	D_2	Be	C	Pb
Lethargy	0.95	0.57	0.75	0.21	0.16	0.01
Mean free path	0.29	2.2	6.0	1.2	2.6	2.7
(cm) $\lambda = 1/(N\sigma_s)$						
Density N ($10^{23}/cm^3$)	0.34	0.33	0.25	1.24	0.80	0.33
Scattering σ_s (b)	103	13.6	6.8	7.0	4.8	11.3
Life time (ms)	0.21	100	177	3.46	13	0.81
$\tau_a = 1/(N\sigma_a v)$						
Absorption σ_a (mb)	665	1.23	1.04	7.6	3.53	171

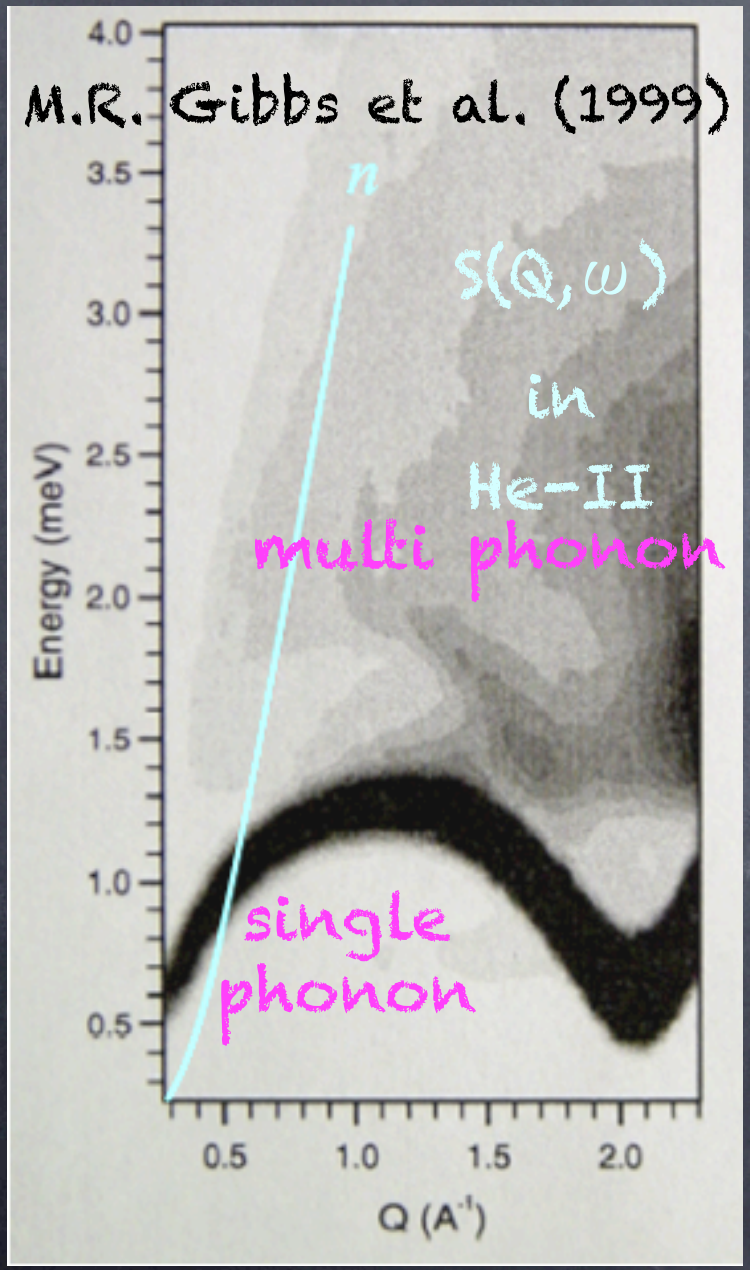
Extraction from source

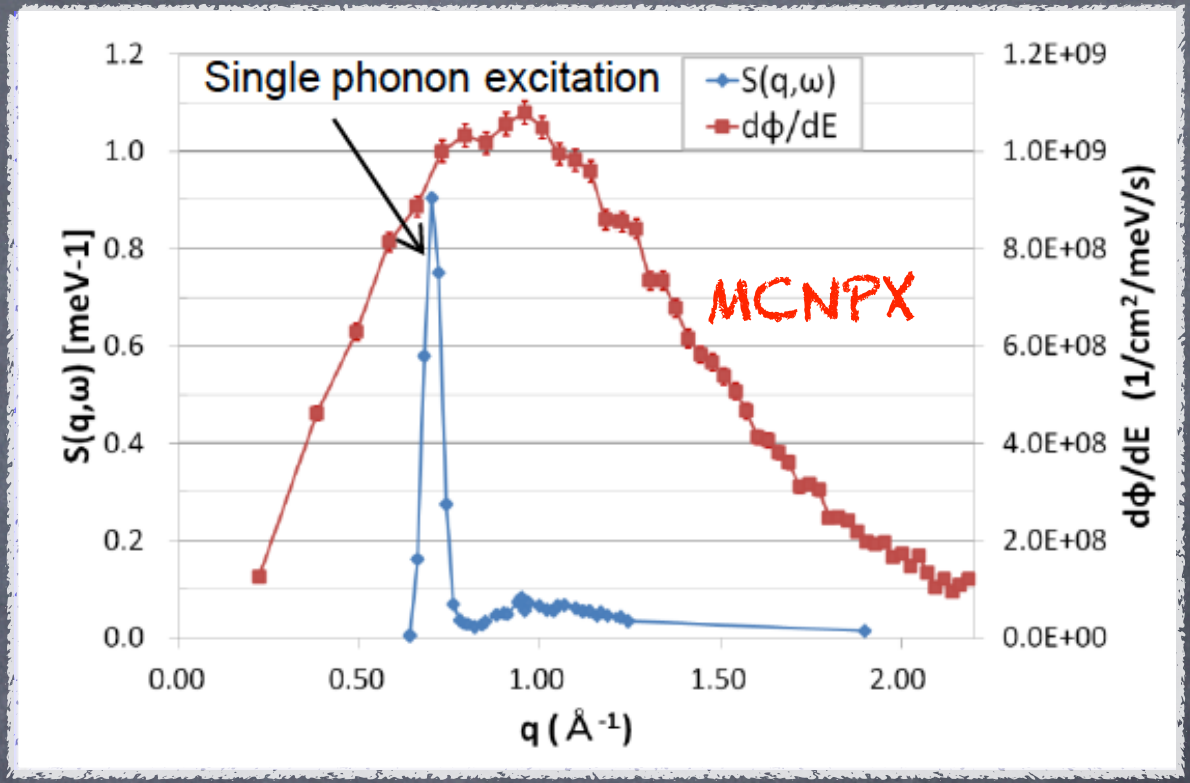


Prototype UCN source: vertical



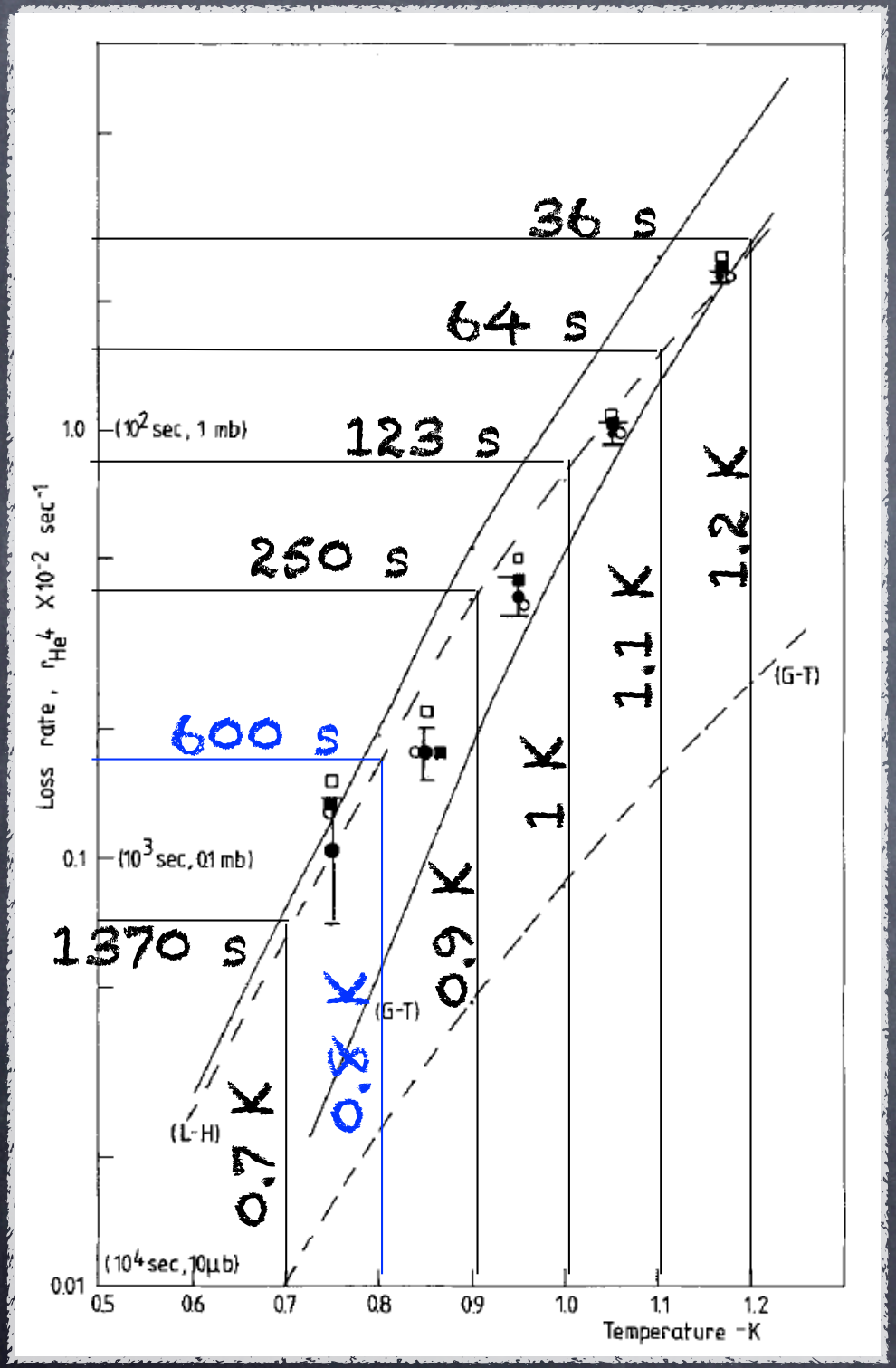
UCN production in He-II





$$P = \int p(E_u)\,dE_u = N_{\mathrm{He}}\,4\pi b^2 \left(\frac{\hbar}{m_n}\right)^2 \frac{k_c^3}{3}\left[\int \frac{d\Phi(q)}{dE} S\left(q, \hbar\omega = \frac{\hbar^2 q^2}{2m_n}\right) dq\right]$$

P = 14 UCN/cm³/s at 20K
= 6 at 50K
= 4 at 80K



UCN lifetime τ_s

He-II [Golub et al. (1983)]

phonon up-scattering, $1/\tau_{ph} \propto T^7$

τ_{ph} = 600 s at 0.8 K

τ_β = 886 s (β decay)

τ_w = 246 s (wall loss)

Z. Phys. B59(1985)261

$\tau_s = 1/\{1/\tau_{ph} + 1/\tau_\beta + 1/\tau_w\}$

= 150 s

SD_2 [Phys.Rev.C71(2005)054601]

τ_{ph} = 40 ms at 8 K

$\tau_{ortho\text{-}para}$ = 100 ms

τ_a = 150 ms

τ_s = 24 ms

diluted with vacuum

→ τ_s = 1.6 s, Los Alamos

→ τ_s = 6 s, PSI

UCN production at RCNP東

P = 4 UCN/cm³·s at E_c = 210 neV for 0.4 kW proton beam

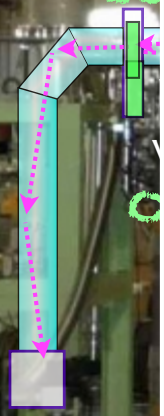
T_s = 81 s

Phys. Rev. Lett. 108(2012)134801

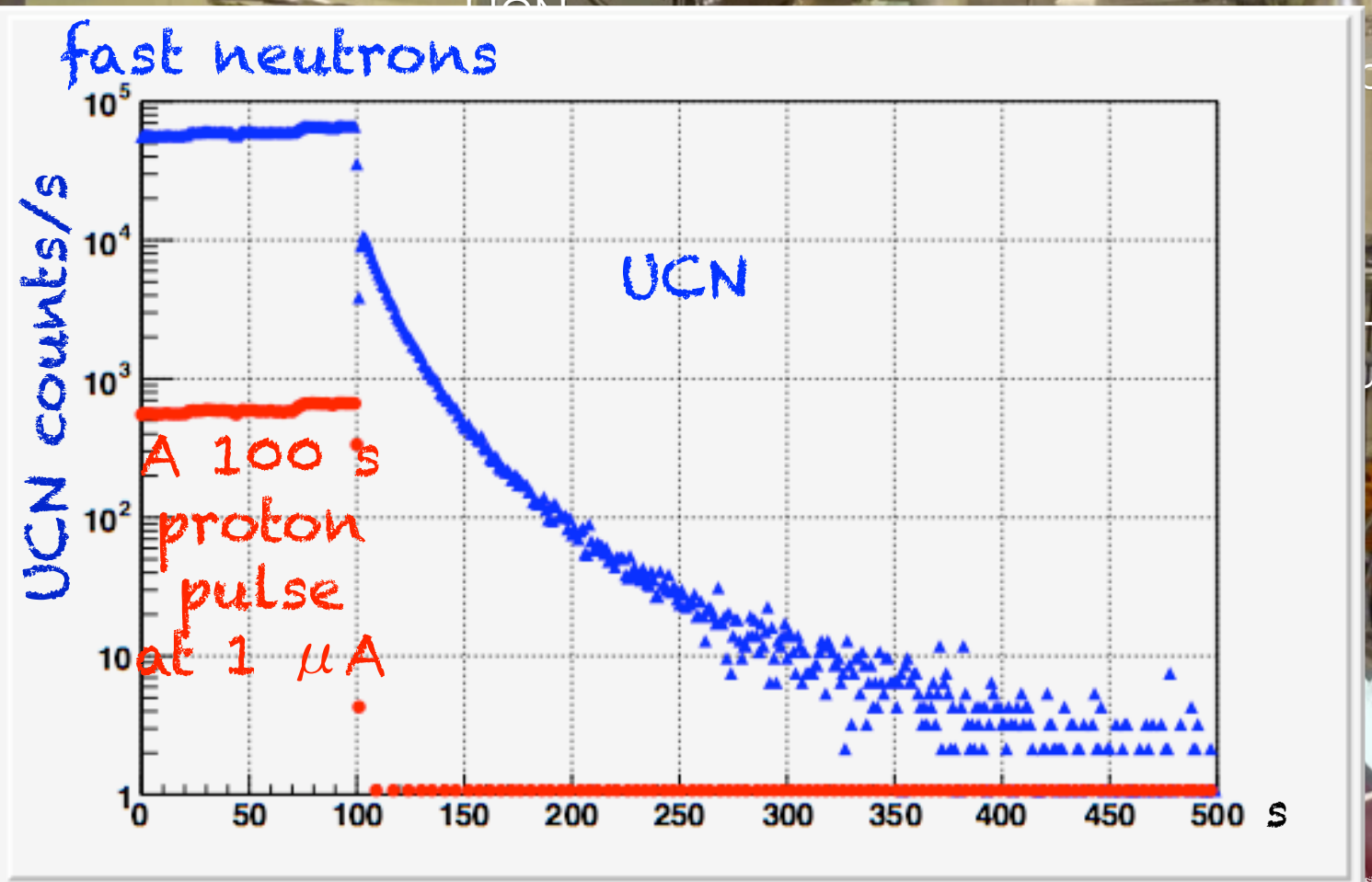
240 s irradiation

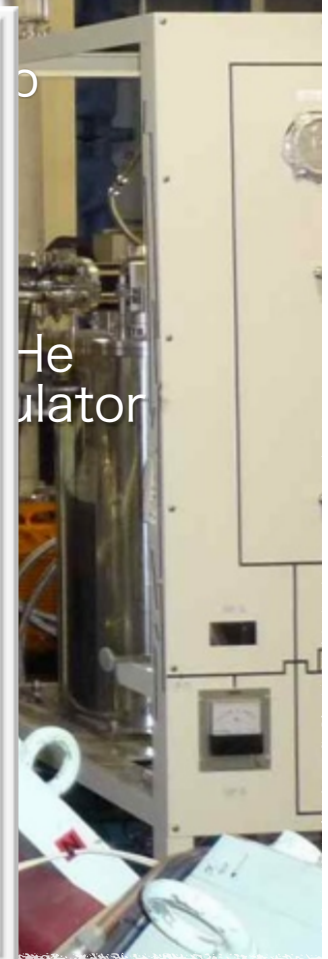
26 UCN/cm³ at E_c = 90 neV,

75 ($\propto E_c^{3/2}$) 180



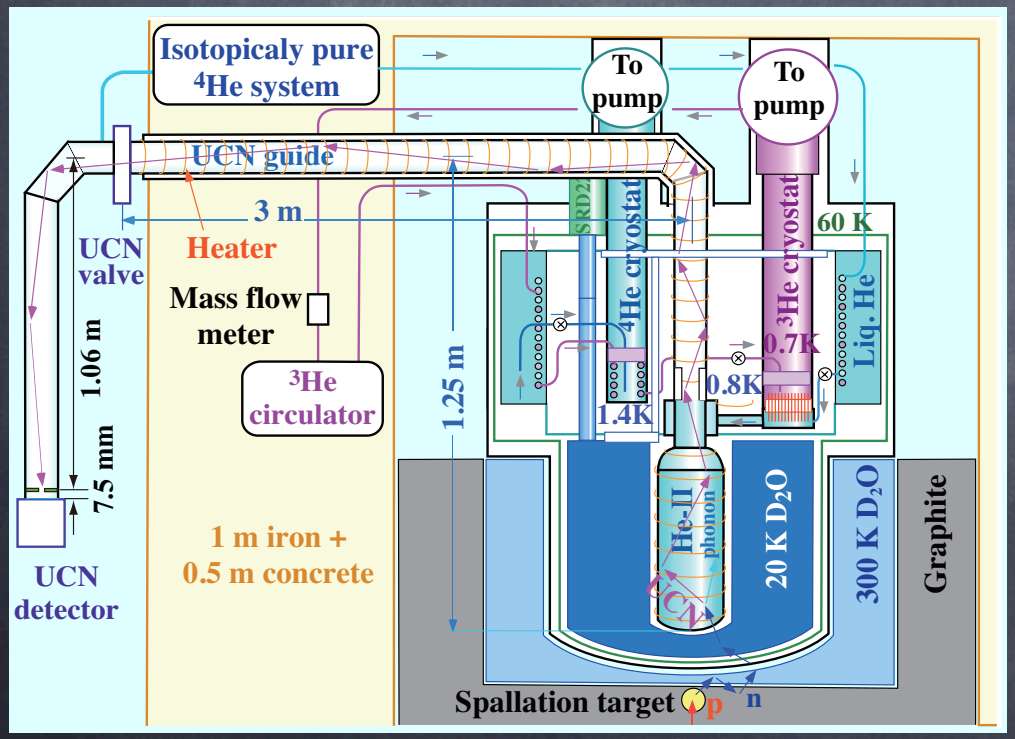
UCN detector

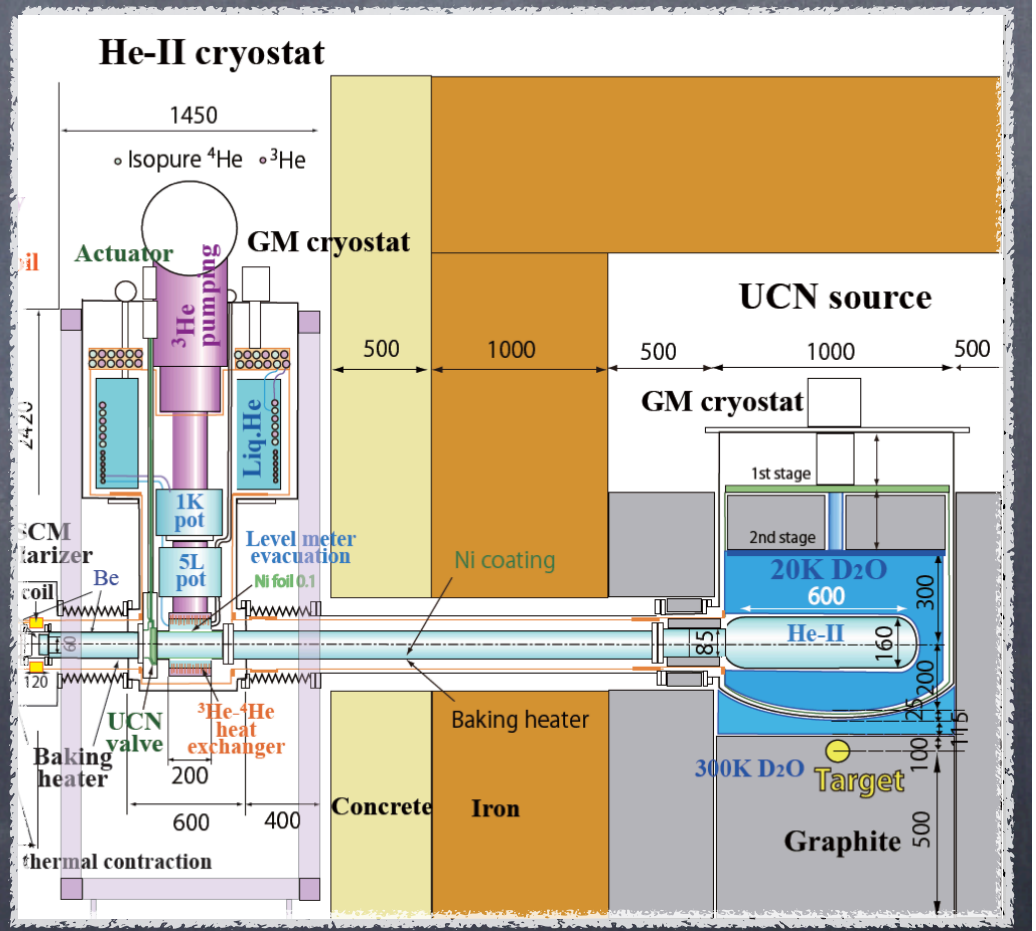




Horizontal He-II for nEDM of 10^{-28} e.cm

Remove the effect of gravity





New UCN source

$$\rho_{UCN} = P\ \tau_s\ \varepsilon_d$$

Vertical UCN source: $P = 4$ UCN/cm^3/s

UCN density in 8L He-II is 320 UCN/cm^3

Phys. Rev. Lett. 108(2012)134801

Horizontal:

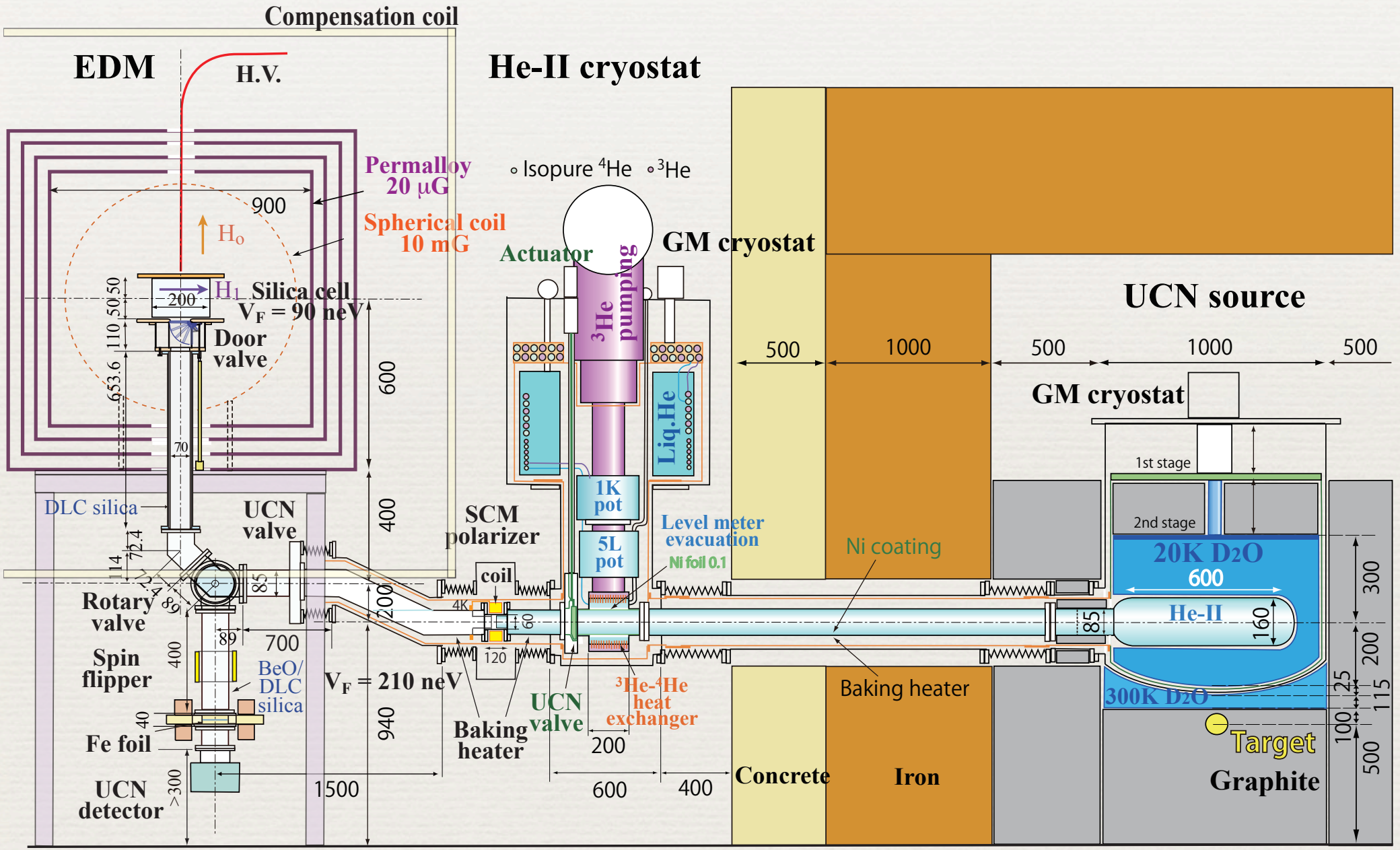
improving geometry	x1.2
increasing RCNP p beam 10μA×400MeV	x10
using TRIUMF p beam 40μA×500MeV	x5
storage lifetime τ_s = 81 s → 150 s	x2

$P\ \tau_s$ = 36000 UCN/cm^3 in 11L He-II

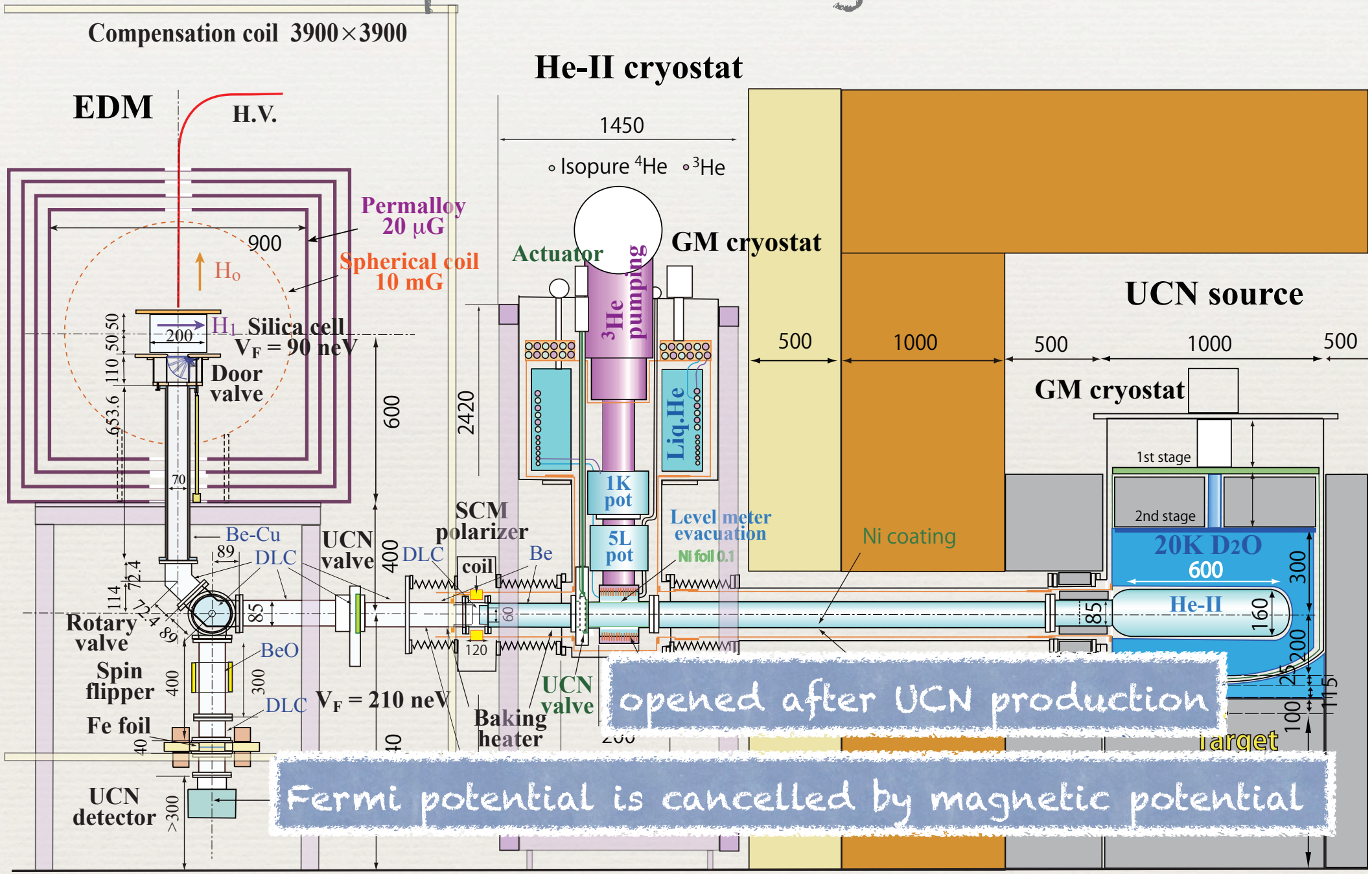
$P\ \tau_s\ \varepsilon_d$ = 12000 UCN/cm^3 at UCN valve in He-II

ε_d : dilution factor

2nd generation source



UCN extraction from He-II through superconducting coil



For γ heating at 500MeV×40μA

γ heating : Monte Carlo Code PHITS

5.2 W in the He-II at a proton power of 20 kW

Cooling power of ^{3}He pumping at 10000 m^3/h

Q	×	P_{He}	×	dV/dt	/ {	R	×	T }	
latent heat of vaporization		vapor pressure		pumping power		gas constant		pump temperature	
34.5 J/mol		1.5 at 0.7 K Torr		1×10^4 m^3/h		8.3×10^{-5} m^{3}bar/(mol.K)		300 K	= 8.5 W
		(τ_{ph} = 1370 s)							
		3 at 0.8 K (600 s)							= 17 W
		6 at 0.9 K (250 s)							= 34 W
		10 at 1 K (123 s)							= 57 W

Temperature difference between ^{3}He and ^{4}He

Kapitza thermal boundary resistance

Lounasmaa, Academic Press (1974)

$R_K = 0.004/T^3/S$ (K/W) at T = 0.8 K, S in m^2

Total surface area of the heat exchanger S = 2 m^2

Sand blasted surface R_K x1/2 (PLA 37, 101(1971))

$R_K = 0.002$ (K/W)

$\delta T = 0.01$ K for $dQ/dT = 5.2$ W

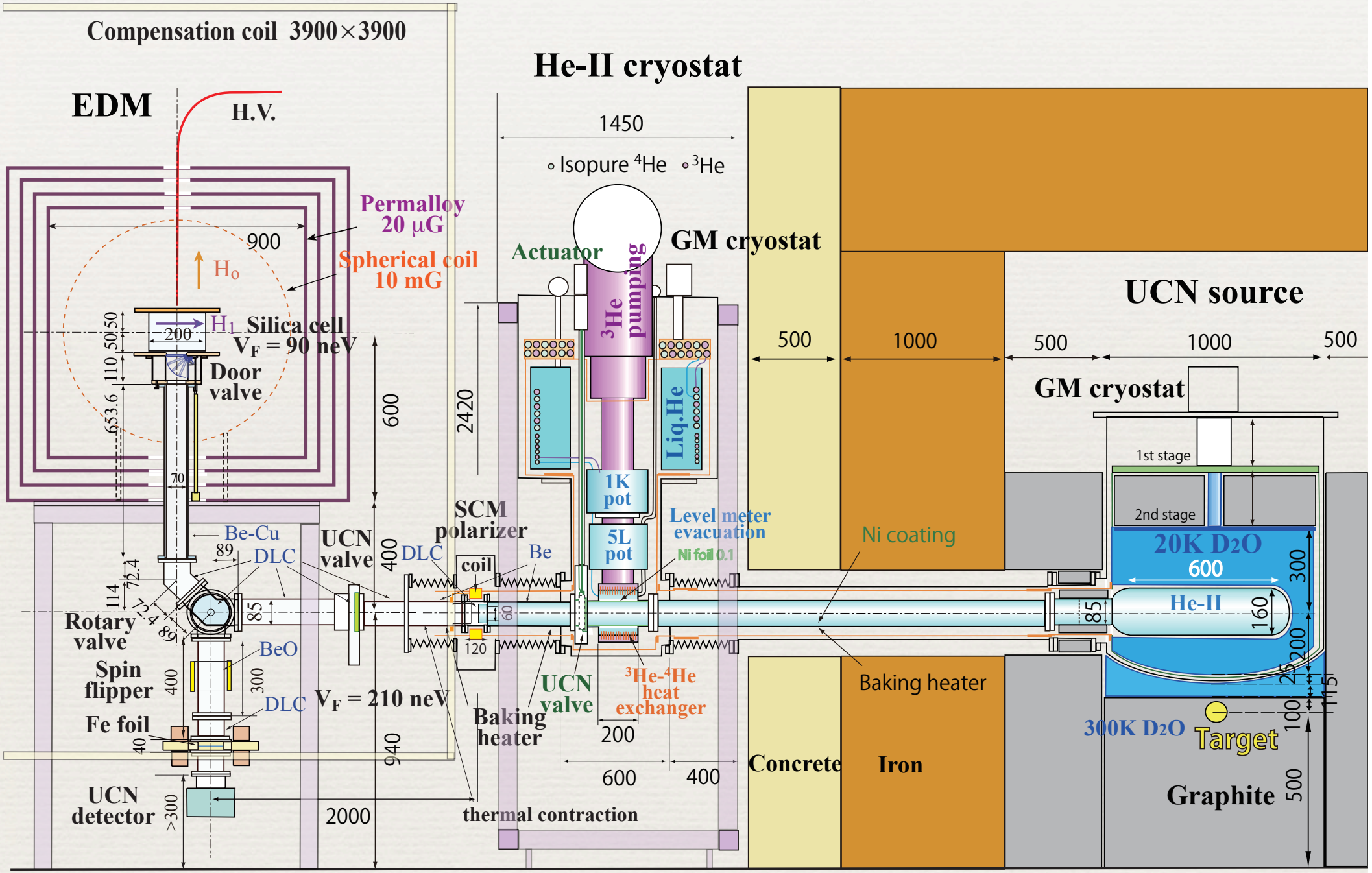
Thermal conductivity in the heat exchanger of 6N Cu

$\delta T = (dQ/dT)/(\kappa \times S/l)$

$\kappa = 25$ W/cm/K at T = 0.8 K, S = 368 cm^2, l = 1 cm

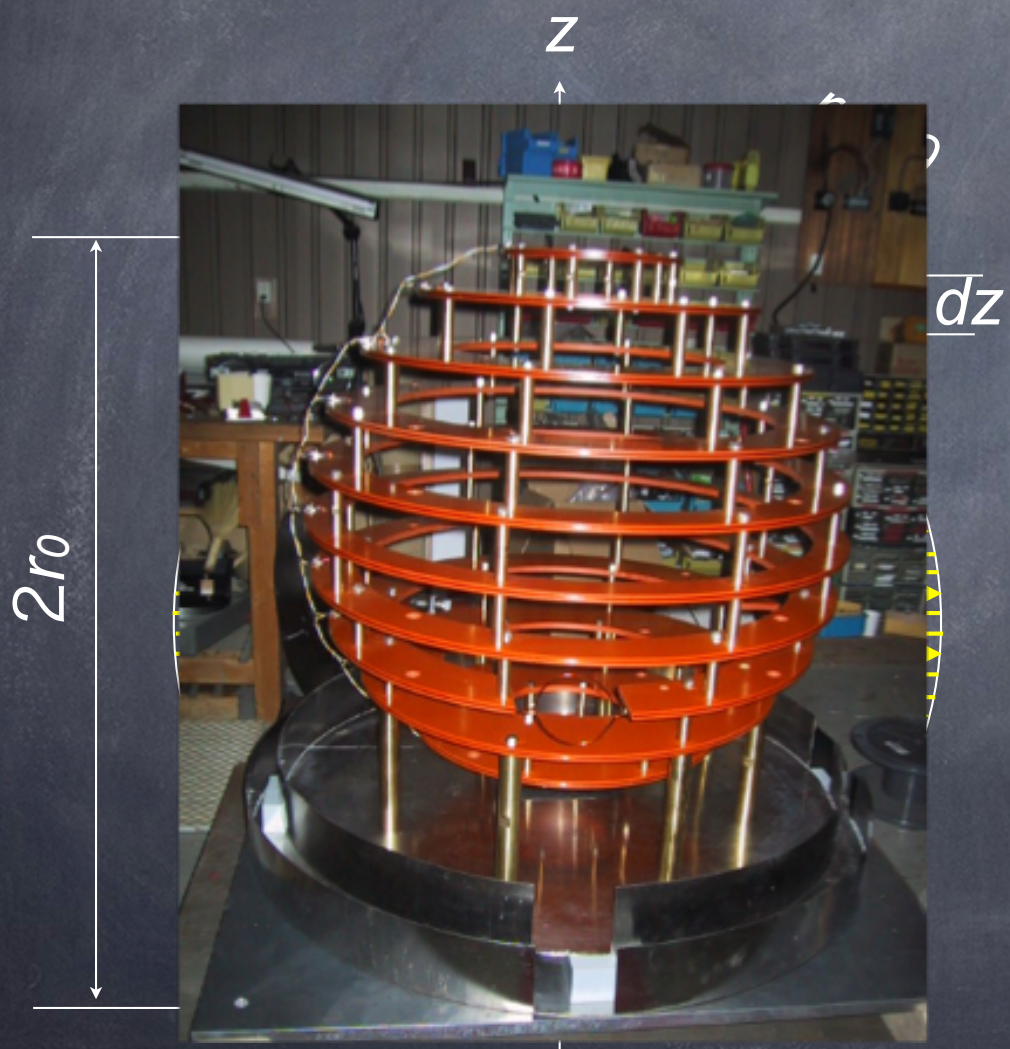
$\delta T = 0.001$ K for 5.2 W

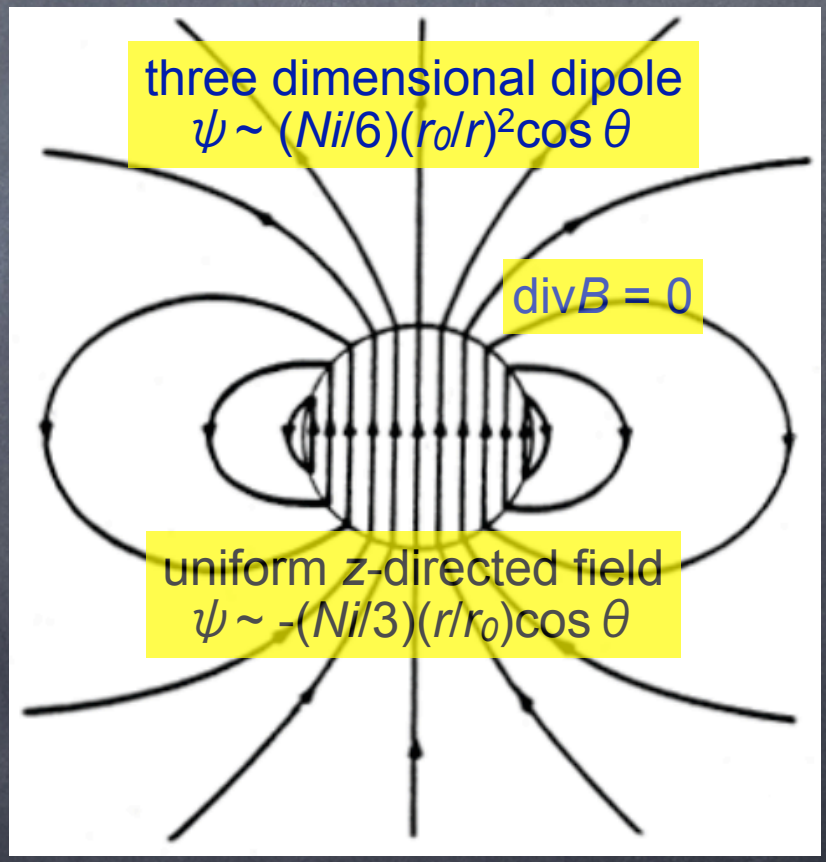
Our nEDM apparatus



Spherical coil, no quadrupole component

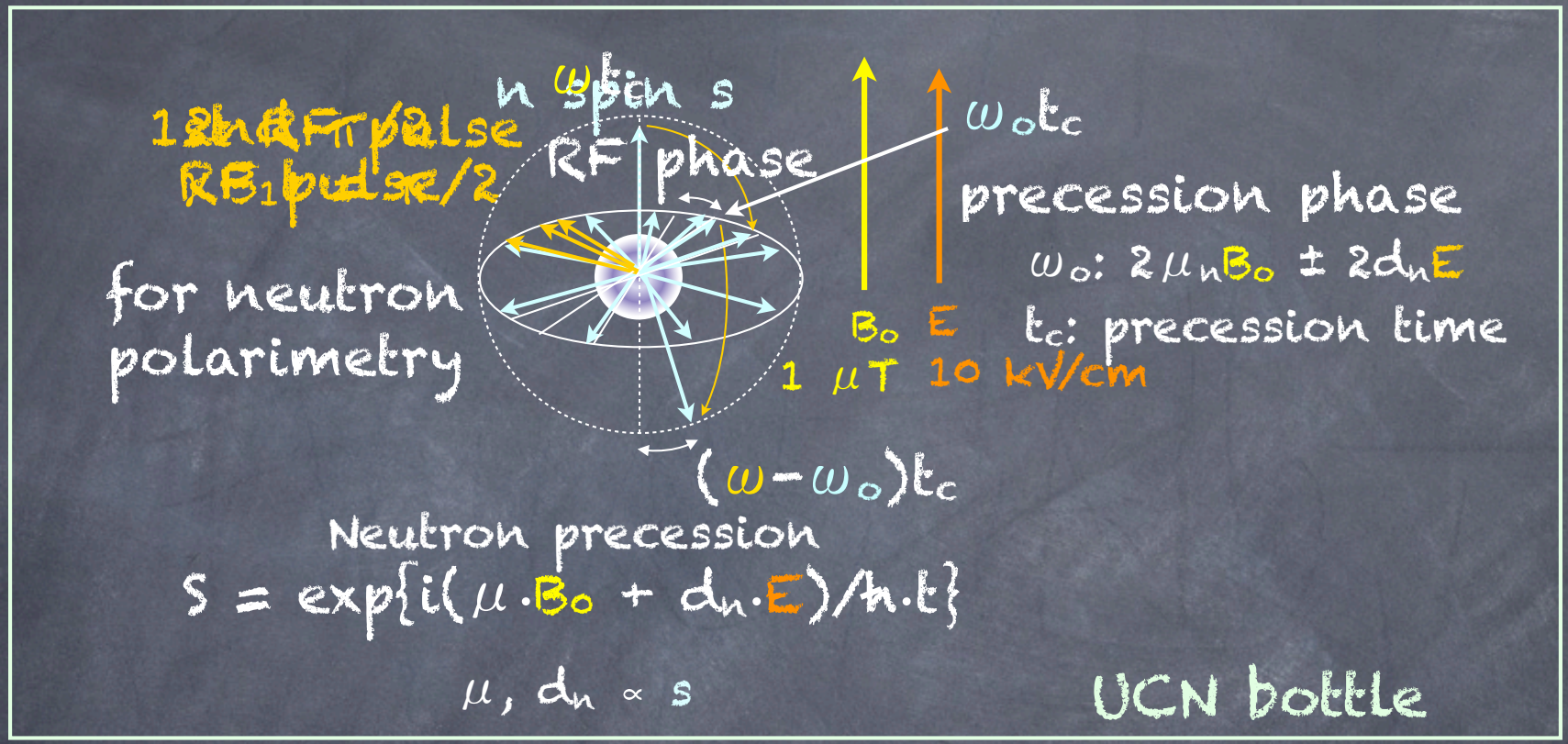
compact apparatus → suppress the cost

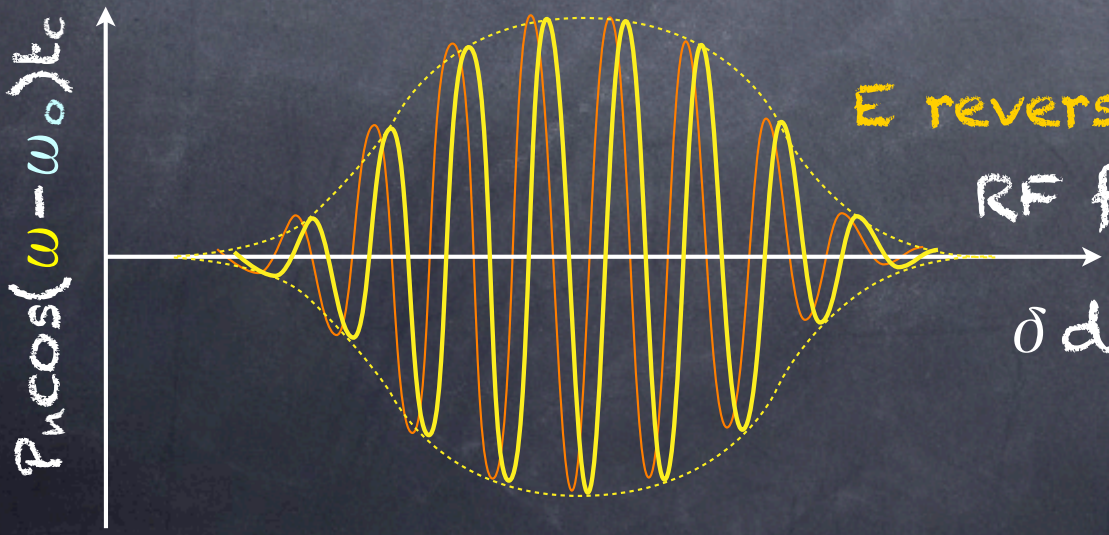




10^{-4} setting and current fine tuning

EDM measurement



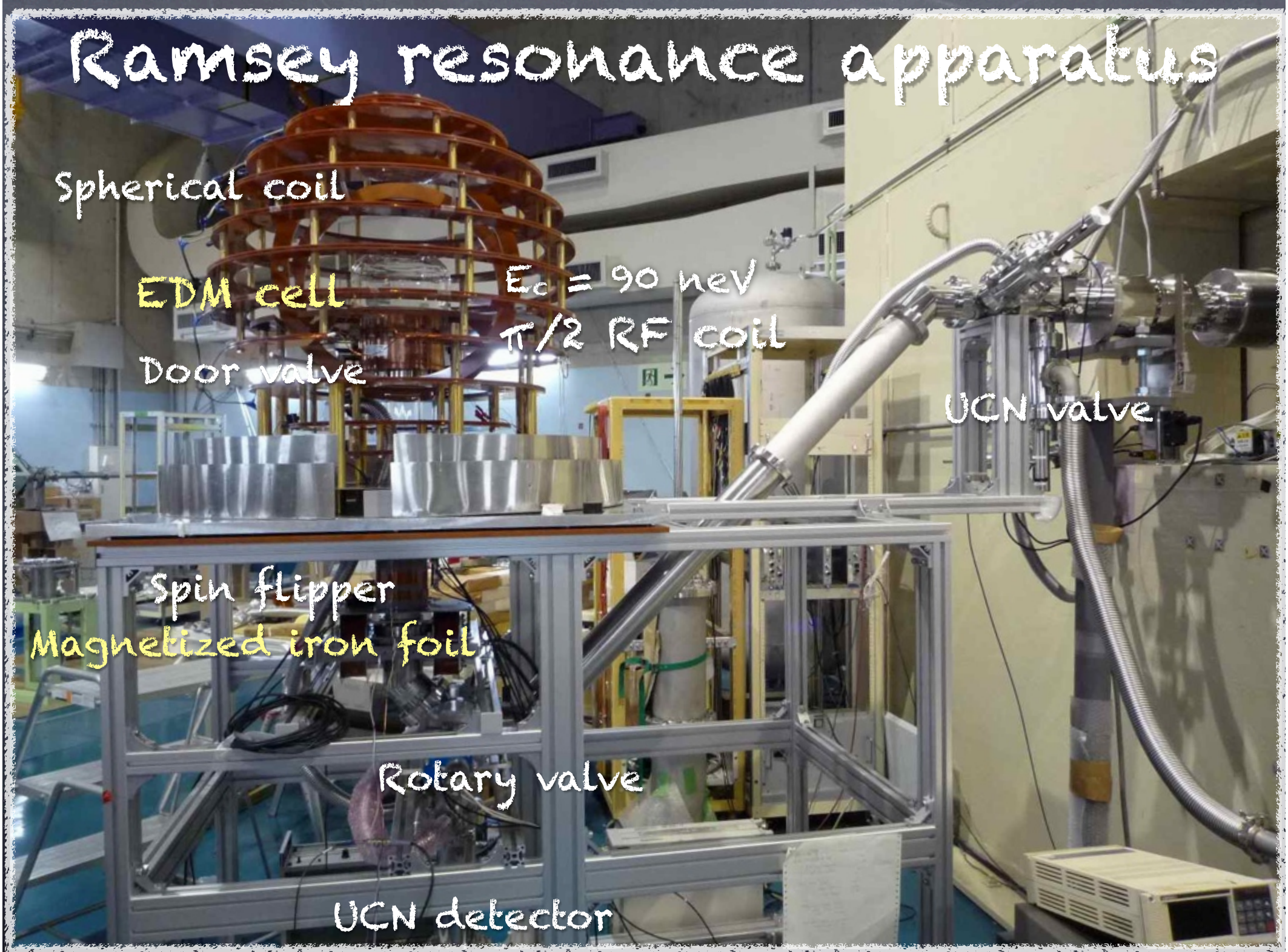


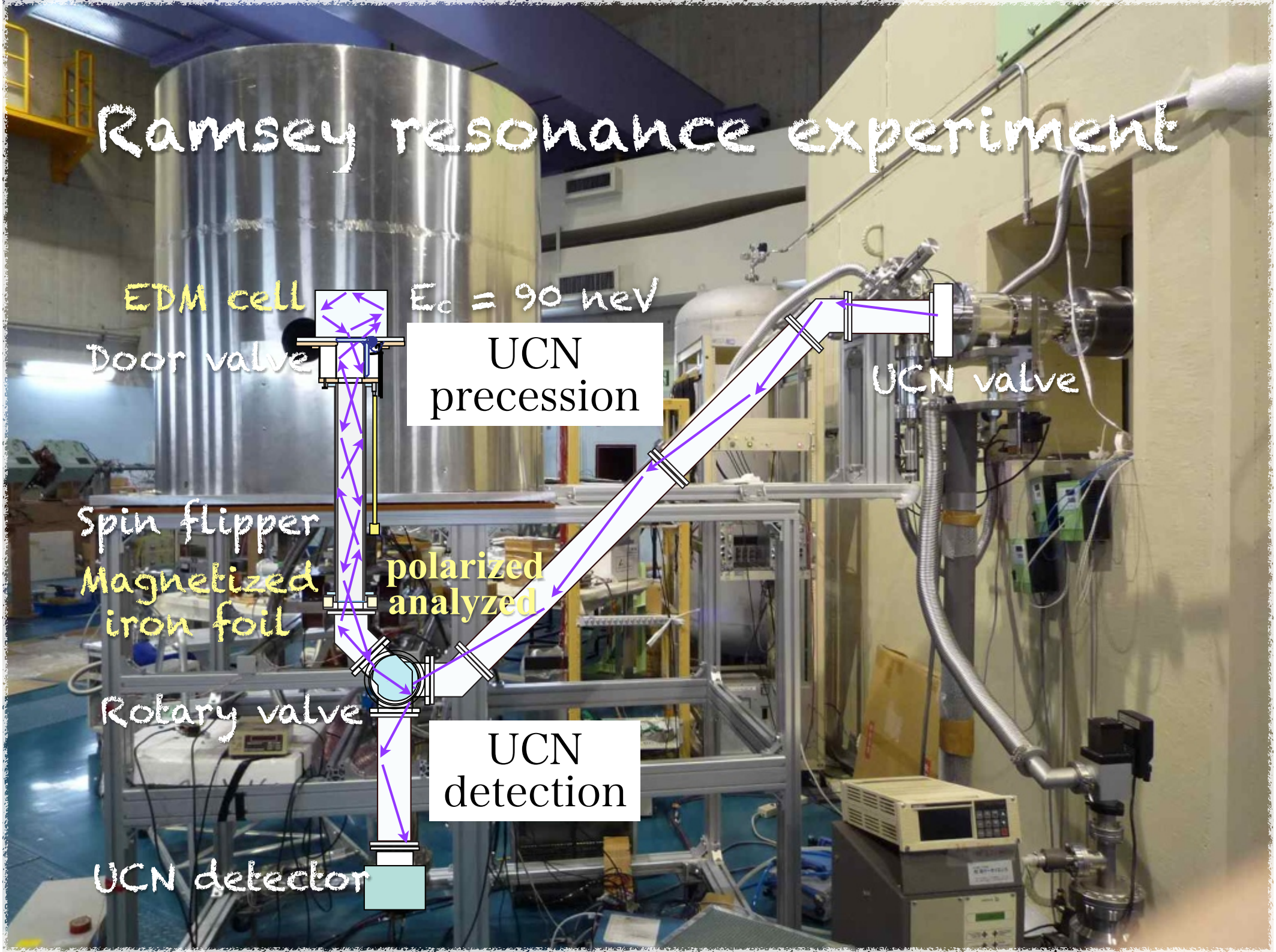
$$\delta d_{sta} = \hbar/\{2P_n E t_c \sqrt{N}\}$$

P_n : UCN polarization

N : number of UCN

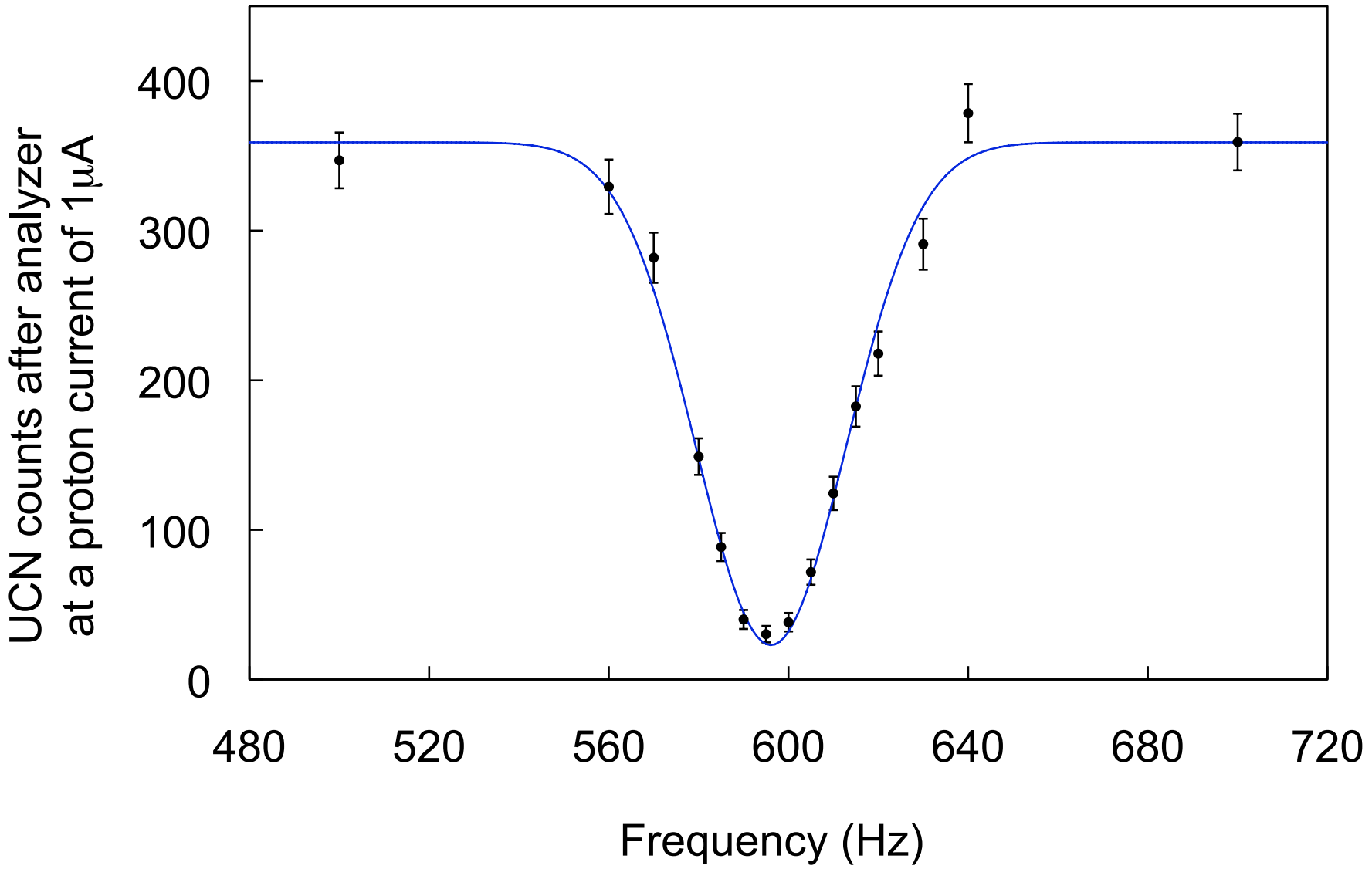
Ramsey resonance apparatus



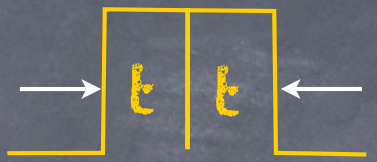

Ramsey resonance experiment
EDM cell
E_c = 90 neV
Door valve
UCN precession
UCN valve
Spin flipper
Magnetized iron foil
polarized analyzed
Rotary valve
UCN detection
UCN detector

UCN NMR in EDM cell

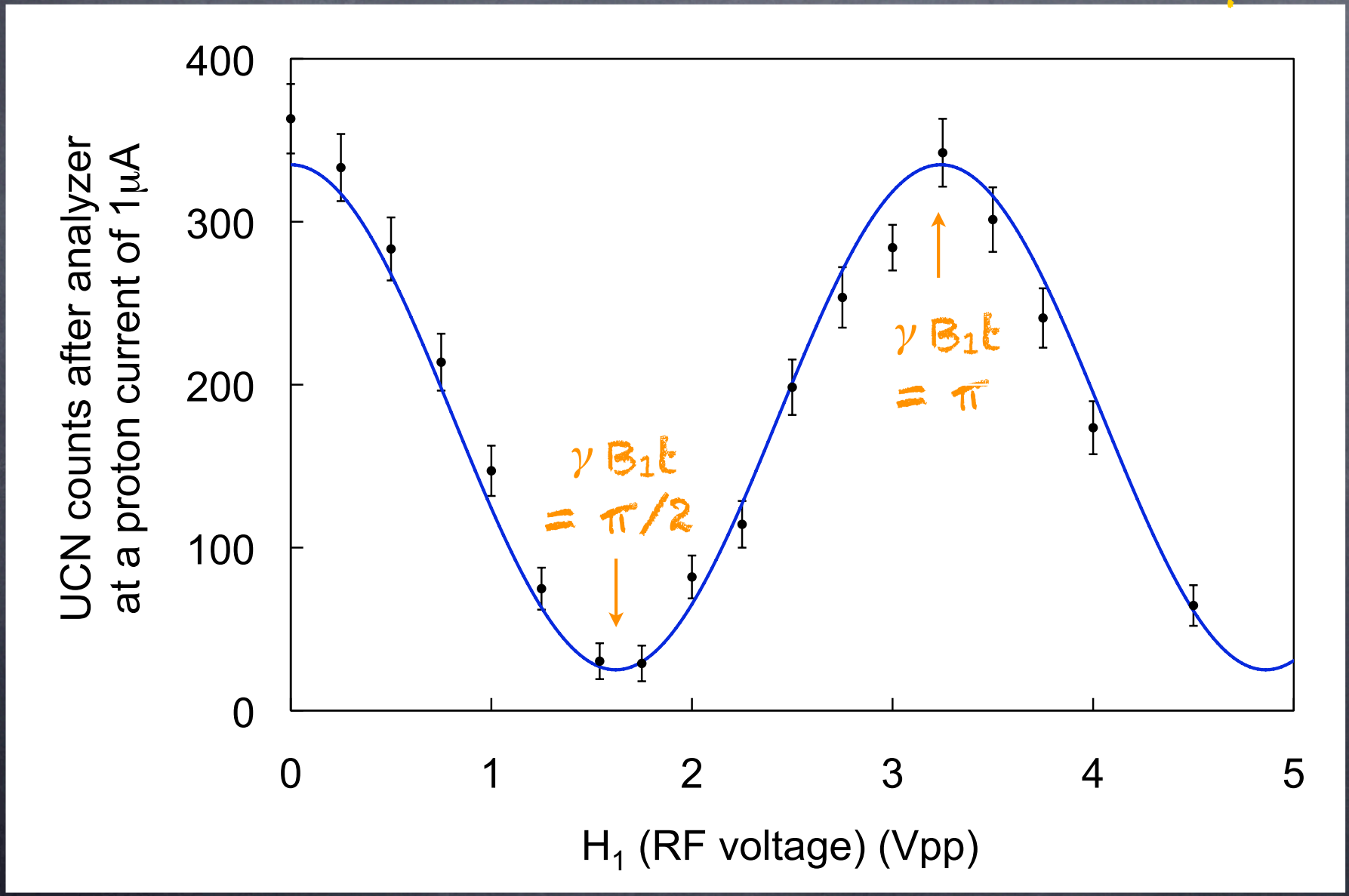
two coherent π/2 RF pulses



UCN spin rotation by $\gamma B_1 t$



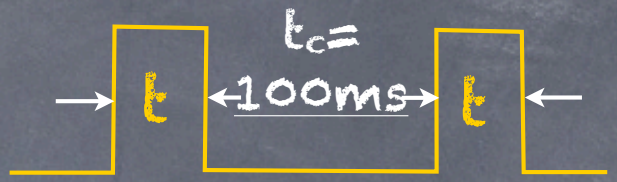
two coherent $\pi/2$ RF pulses



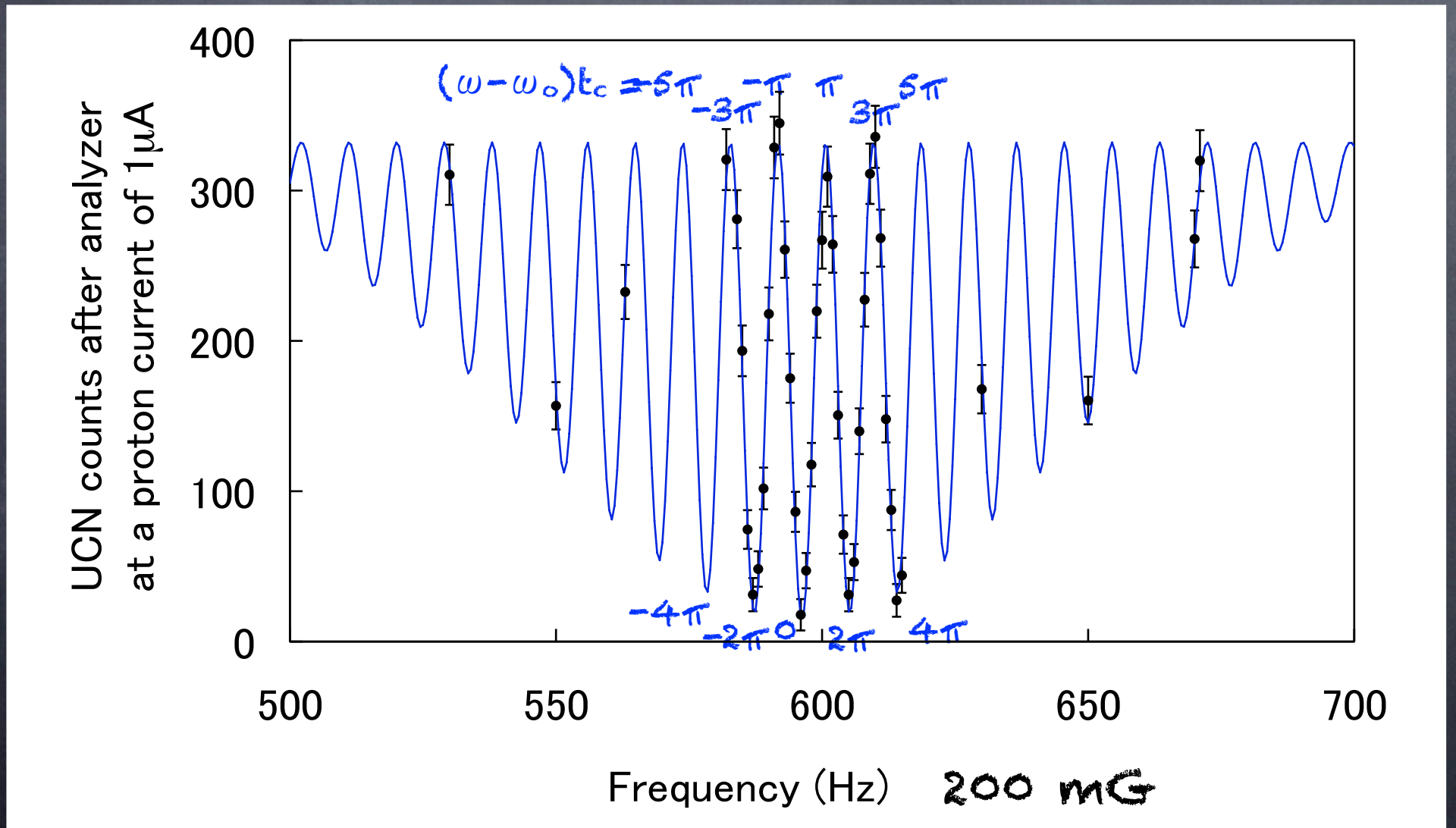
Ramsey resonance

visibility α =

$(N_{max} - N_{min})/(N_{max} + N_{min}) = 0.9$



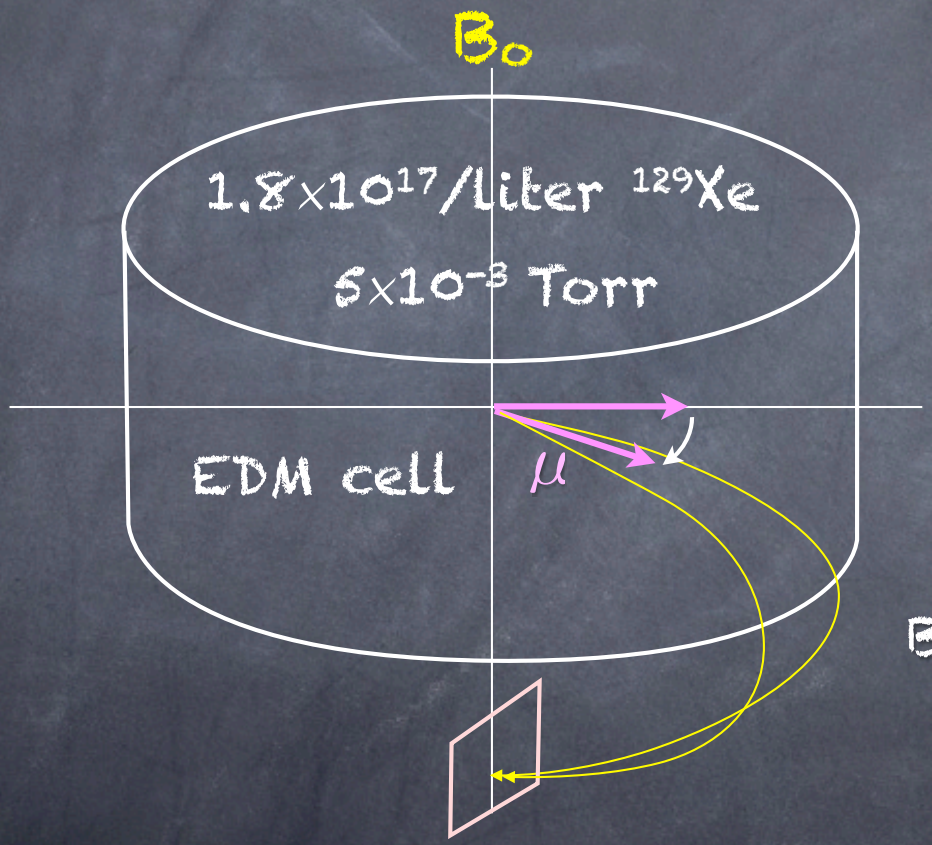
two coherent $\pi/2$ RF pulses



B_0 monitor by nuclear spin precession

Isotope	J_N	$g(\gamma_N = g\mu_N/\hbar)$	σ_a at 2200 m/s	ρ for $\tau = 1/(\sigma_a \rho v) = 500$ s
^{129}Xe Ours	1/2	-0.777	21 b	2.5×10^{14}/cc, Rb-Xe photon
^{199}Hg ILL	1/2	0.5026	2150 b	(3×10^{10}/cc, photon)
n cryoEDM	1/2	-1.913		
^{3}He SNS	1/2	-2.128	5333 b	10^{12}/cc, SQUID
^{133}Cs PSI	7/2	2.579	29 b	

^{129}Xe spin magnetometer



^{129}Xe magnetization

$P_{^{129}Xe} = 0.5$

$B = 0.4$ pT
in the EDM cell

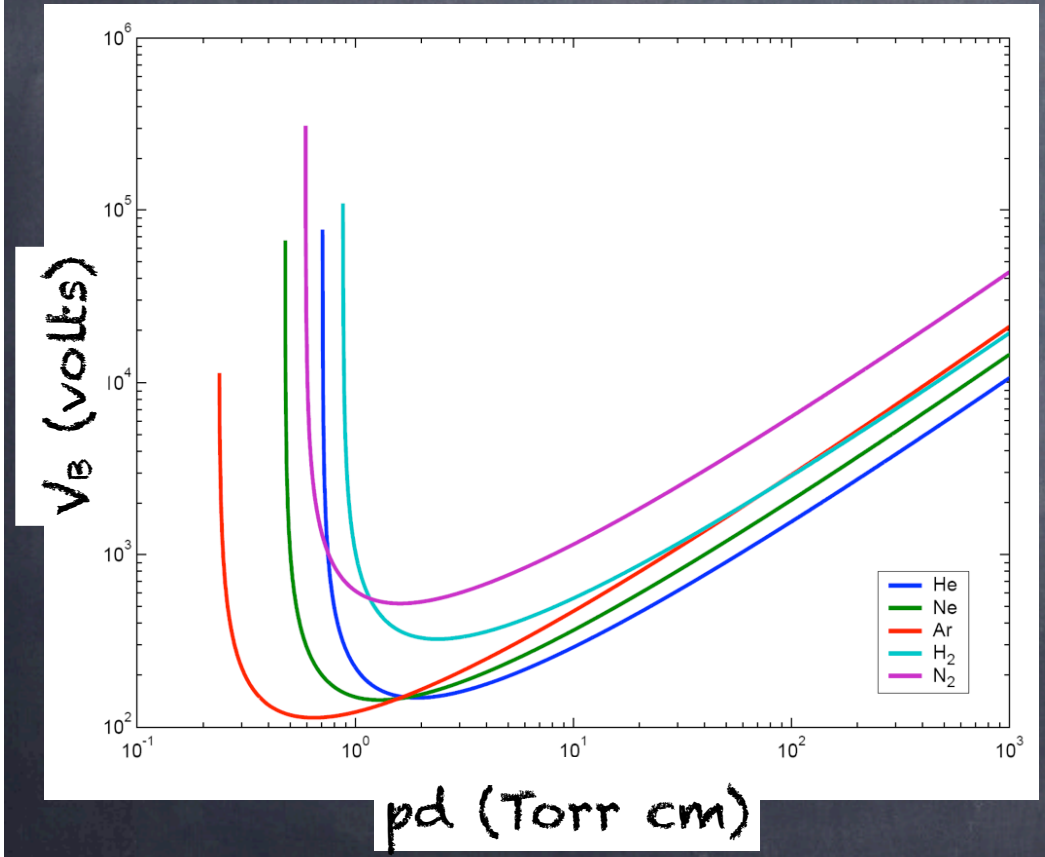
Rb–^{129}Xe
van der Waals
molecule

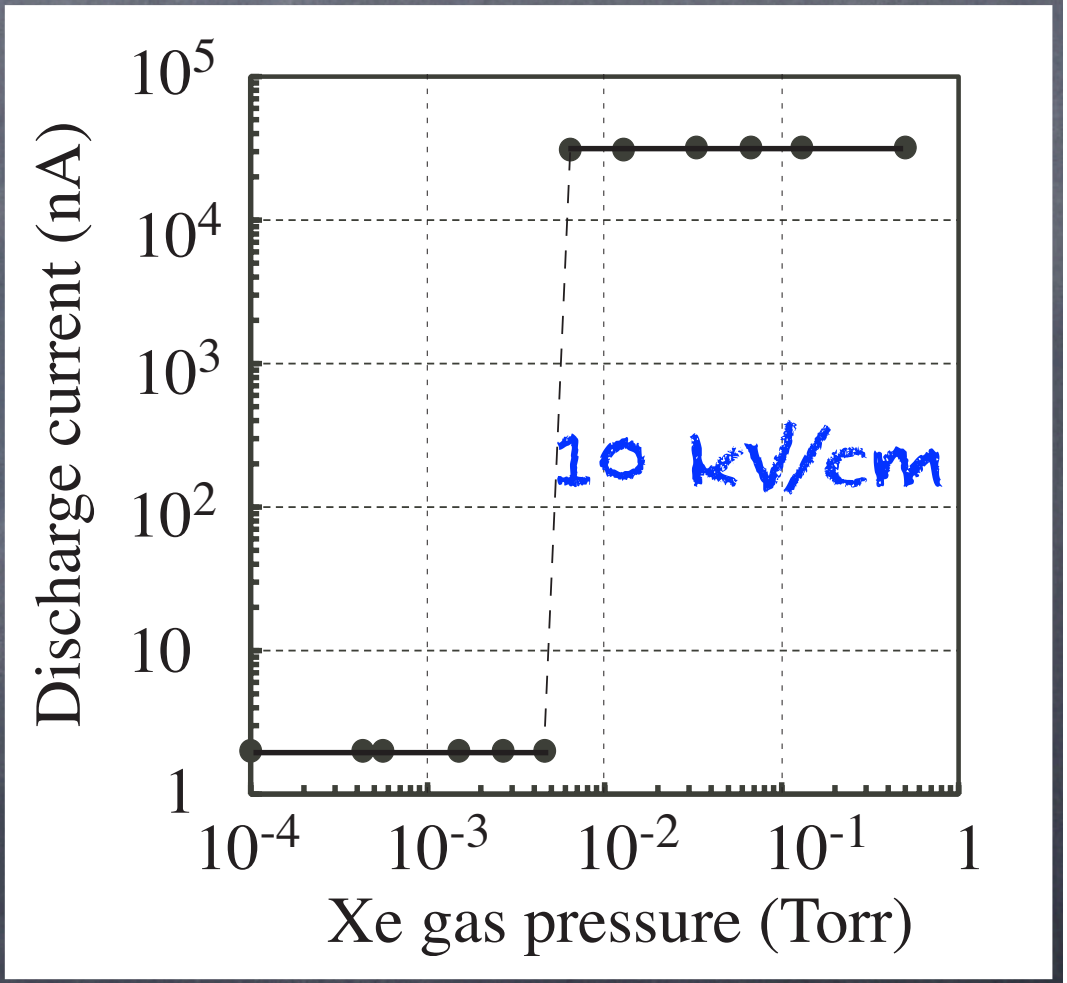
$B = 0.15$ pT
at 0.1 m
from the center

SQUID 1fT, $5\,\mu\Phi_o/\sqrt{Hz}$

High voltage break down at 5×10^{-3} torr ?

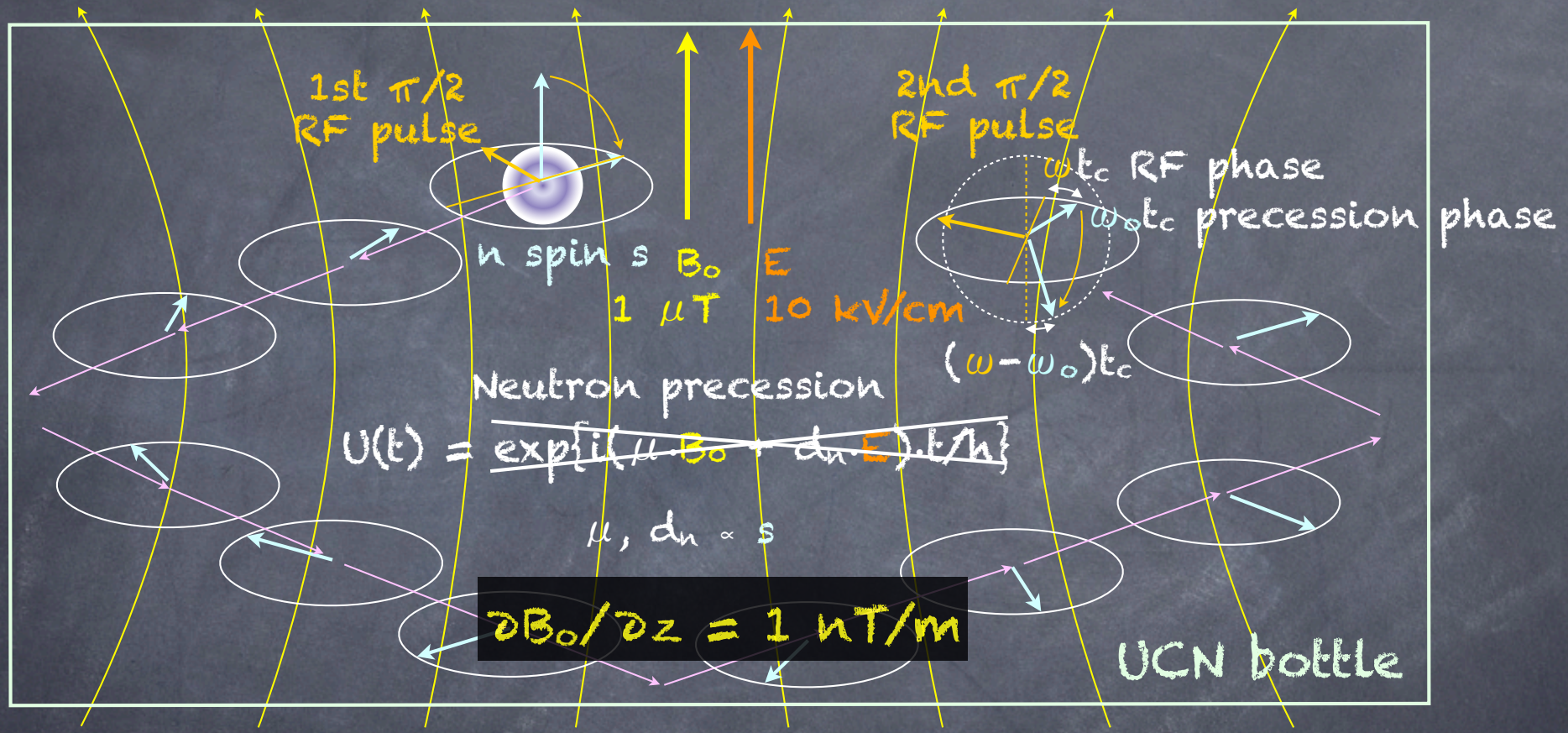
Paschen's law





Phys. Lett. A 376(2012)1347

Geometric phase effect (GPE)



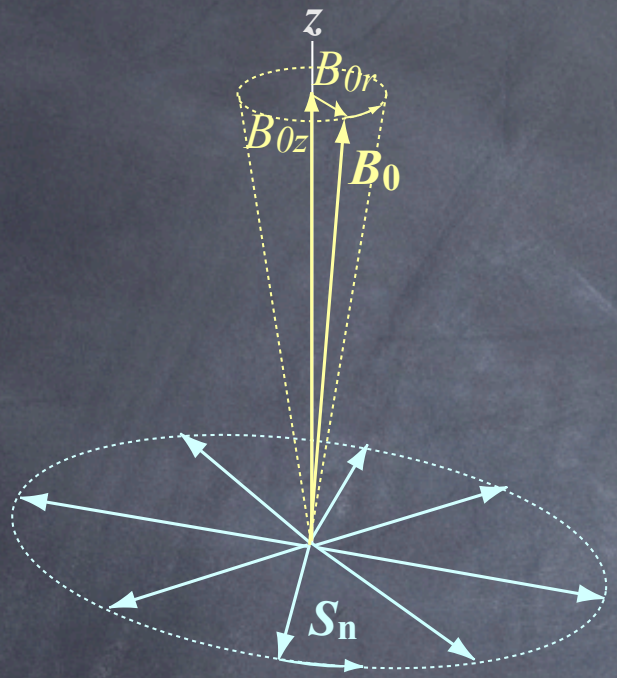
Geometric phases arise from the transverse fields,

$\{(\partial B_o/\partial z)r/2 + E\times v/c^2\}^2$

Pendlebury, Phys. Rev. A70(2004)032102.
Lamoreaux, Phys. Rev. A71(2005)052115.

Effect of time dependent interaction

Phys.Lett. A376(2012)1347



$$U(t) = \exp(-iH_0 t/\hbar)$$

$$H_0 = -\boldsymbol{\mu}\cdot\boldsymbol{B}_0 - \boldsymbol{d}_n\cdot\boldsymbol{E}$$

$$H = H_0 + V(t)$$

$$V(t) = -\boldsymbol{\mu}\cdot\boldsymbol{B}_{xy}(t) = -\gamma\boldsymbol{s}\cdot(\boldsymbol{B}_v(t) + \boldsymbol{B}_{0r}(t))$$

$$\boldsymbol{B}_v = \boldsymbol{E}\times\boldsymbol{v}/c^2 \quad \boldsymbol{B}_{0r} = -(\partial B_{0z}/\partial z)\boldsymbol{r}/2$$

$$U_I(t) = 1 + (\frac{-i}{\hbar})\int_0^t dt' V_I(t') + (\frac{-i}{\hbar})^2\int_0^t dt'\int_0^{t'} dt'' V_I(t')V_I(t'') + \cdots$$

$$V_I(t) = \exp(iH_0 t/\hbar)\{-\boldsymbol{\mu}\cdot\boldsymbol{B}_{xy}(t)\}\exp(-iH_0 t/\hbar)$$

$$U_I(t) = 1 + \frac{is_z}{\hbar}\frac{1}{4}\gamma^2\frac{E}{c^2}\frac{\partial B_{0z}}{\partial z}\int_0^t dt'\int_0^{t'} d\tau\cos(\omega_0\tau)$$

$$\{x(t')v_x(t'-\tau) - x(t'-\tau)v_x(t') + y(t')v_y(t'-\tau) - y(t'-\tau)v_y(t')\}$$

similar form as Lamoreaux and Golub, Phys. Rev.A71(2005)052115.

Solution for GPE problem

$$\int_0^t d\tau \cos(\omega_0 \tau)\{x(t')v_x(t'-\tau) - x(t'-\tau)v_x(t') + y(t')v_y(t'-\tau) - y(t'-\tau)v_y(t')\}$$

$d_{afHgn} = \hbar/8 \cdot \gamma_n \gamma_{Hg} (\partial B_{oz}/\partial z) R^2/c^2$

5×10^{-26} e cm at R = 25 cm

$d_{afn} = -\hbar/4 \cdot (\partial B_{oz}/\partial z)/B_{oz}^2 \cdot v_{xy}^2/c^2$

1×10^{-27} e.cm at 1nT/m, 1 μT

^{129}Xe mean free path

$\lambda = 1/n\sigma$ 0.7~5 mm

r(t) almost constant

v(t−τ) rapidly change

$\langle r(t)v(t-\tau)\rangle \rightarrow \ll 1$

$(0.59\omega_o R^2/v_{xy}\lambda)^2$

$(\partial B_{oz}/\partial z)/B_{oz}^2$

→ x 1/10

$d_{afXen} \rightarrow 10^{-28}$ e.cm

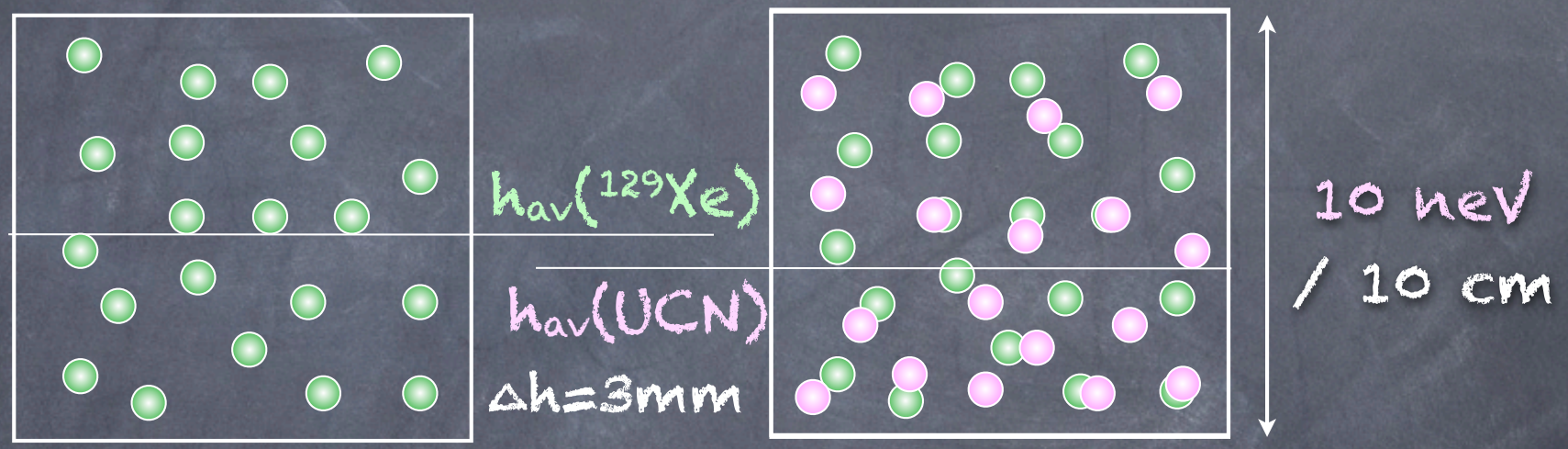
$d_{afn} \rightarrow 10^{-28}$ e.cm

Field gradient control

develop Pendlebury's approach

^{129}Xe: v_{129Xe} 240 m/s

UCN: v_{UCN} 5 m/s



$\omega_{129xe} = \gamma_{129xe}B(h_{129Xe})$, $\omega_n = \gamma_n B(h_n)$

Assuming cylindrical symmetry

$(\omega_n/\gamma_n)/(\omega_{129Xe}/\gamma_{129Xe}) = 1 + \delta\gamma + \delta z(\partial B_{oz}/\partial z)/B_{oz}$

Free from earth's rotation

Precision g factor measurement

Phys.Lett. A376(2012)1347

$(\omega_n/\gamma_n)/(\omega_{129Xe}/\gamma_{129Xe}) = 1 + \delta\gamma + \delta z(\partial B_{oz}/\partial z)/B_{oz}$

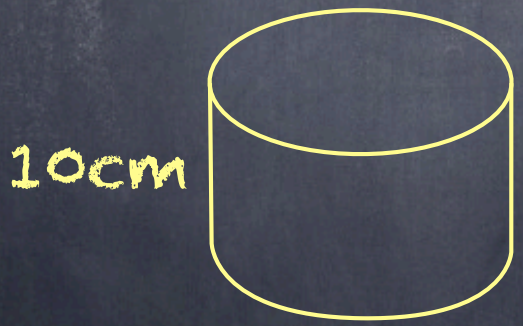
1 mm x 5 nT/m / 50 μT = 10^{-7}

δz = 1 mm

The value of $\delta\gamma$ can be obtained with 10^{-7} in a cell of 3 cm hight

$\omega_{3He}/\omega_{129Xe}$ is better because δz is smaller

The uncertainty of 10^{-7} is much smaller than ^{199}Hg.



δz = 3 mm

$\delta z(\partial B_{oz}/\partial z)/B_{oz}$ =
3mm x 0.1 nT/m / 1μT = 3 x 10^{-7}
precision of $\partial B_{oz}/\partial z$ becomes 0.1 nT/m

$d_{afn} = -\hbar/4 \cdot (\partial B_{oz}/\partial z)/B_{oz}^2 \cdot v_{xy}^2/c^2 \rightarrow < 1 \times 10^{-28}$ e.cm

Process to $\partial B_{oz}/\partial z = 0$

$$B_o(x,y,z) = \delta B + c^i I_{coil}{}^i$$

δB : remnant magnetization around the EDM cell, which may change upon magnetic shield opening

We use a atomic, for example potassium magnetometer to remove dipole fields around the EDM cell

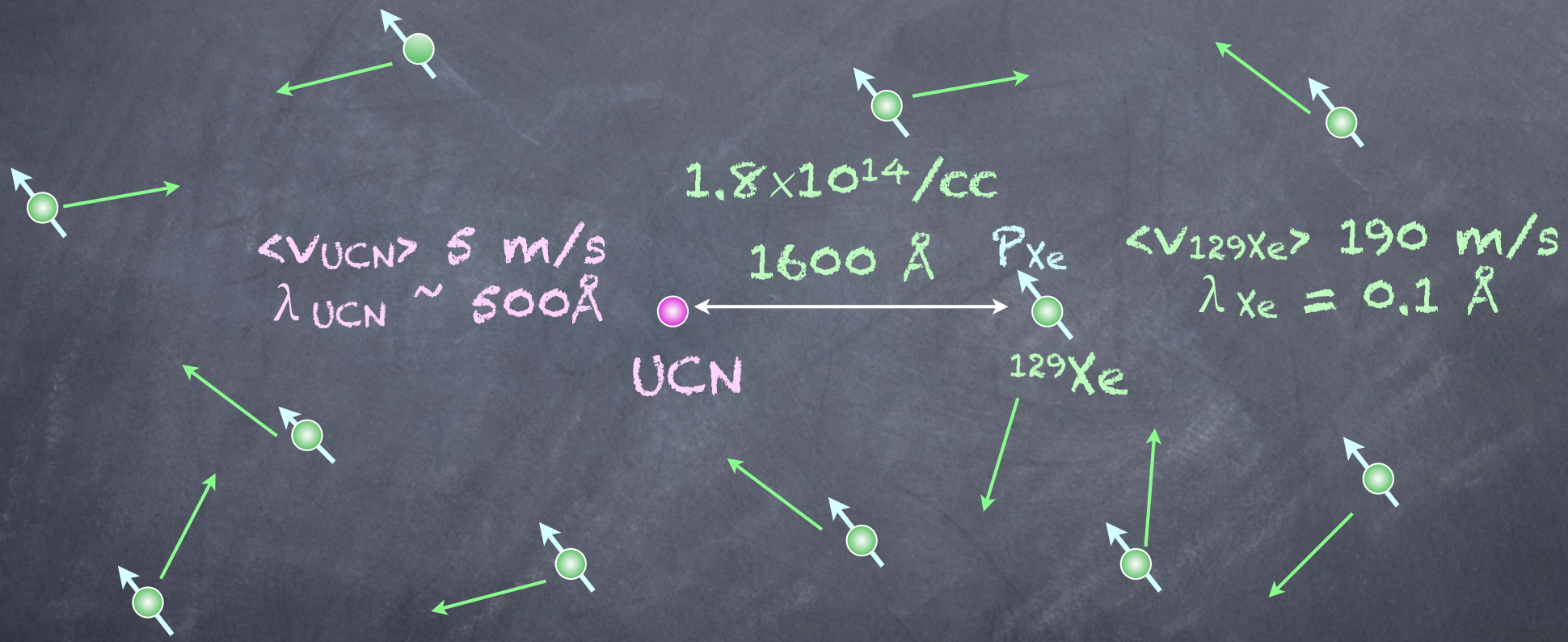
Frequency ratio measurement after closing the shield

$$(\omega_n/\gamma_n)/(\omega_{129Xe}/\gamma_{129Xe}) = 1 + \delta\gamma + \delta z(\partial B_{oz}/\partial z)/B_{oz}$$

$$\delta\gamma = 10^{-7}$$

Spin dependent nuclear interaction?

^{129}Xe pseudo magnetism 0.4 nT > B_{or} = 0.1 nT



Even if coherence remains,
time variation of B_p, ω_{129Xe} and $E \times v/c^2$, ω_r are out of phase. Dyson series calculation shows the effect is small

Pseudo magnetic rotation

$$\boldsymbol{B}_{xy}(t) = \exp(-\frac{is_z\omega_r t}{\hbar})\boldsymbol{B}_v(0)\exp(\frac{is_z\omega_r t}{\hbar}) + \exp(-\frac{is_z\omega'_0 t}{\hbar})\boldsymbol{B}_p(0)\exp(\frac{is_z\omega'_0 t}{\hbar})$$

$$V_I(t) = -\frac{\mu B_v}{\hbar}[\exp\{\frac{is_z(\omega_0-\omega_r)t-\delta}{\hbar}\}s_x\exp\{\frac{-is_z(\omega_0-\omega_r)t+\delta}{\hbar}\}]$$

$$-\frac{\mu B_p}{\hbar}[\exp\{\frac{is_z(\omega_0-\omega'_0)t}{\hbar}\}s_x\exp\{\frac{-is_z(\omega_0-\omega'_0)t}{\hbar}\}]$$

$$\delta\omega = (\gamma_n^2 B_v B_p / 2t)[\{1/(\omega_0-\omega_0')+1/(\omega_0-\omega_r)\}$$
$$\times\{1/(\omega_0'-\omega_r)\}\{\sin((\omega_0'-\omega_r)t-\delta)+\sin\delta\}$$
$$-(\gamma_n^2 B_v B_p / 2t)[\{1/(\omega_0-\omega_0')\}\{1/(\omega_0-\omega_r)\}$$
$$\times\{\sin((\omega_0-\omega_r)t-\delta)+\sin((\omega_0-\omega'_0)t+\delta)\}]$$

systematic error < 10^{-28} e.cm

Collaborators

T. Adachi, Y. Makita, H. Takahashi, K. Tanaka, (KEK), K. Asahi (TIT), D. Nishimura (Osaka),
I. Tanihata (Beihang, RCNP)
D. Ramsay (TRIUMF), S. Page (Manitoba), Momose (UBC), E. Korkmaz (UNBC), M. Barnes (CERN)
R. Golub, E. Korobkina (North Carolina)

Thanks