Spallation UCN production for nEDM

Y. Masuda (KEK), March 26, 2013, Grenoble

EDM measurement

1. Statistical error was limited by UCN density. We need to break through this limitation from Liouville's theorem.

2. Systematic error is dominated by the geometric phase effect. We need a new magnetometer.

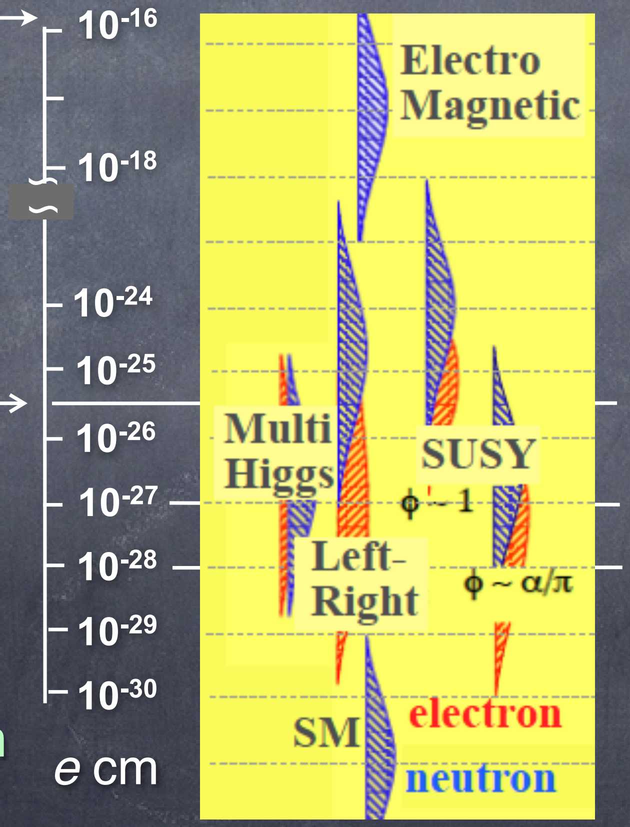
We will discuss our approach.

KEK-RCNP nEDM measurement

Earth's field
($\mu_n H_0/E$)

ILL
EDM upper limit

statistical error:
1.5×10^{-26} *e* cm
systematic error:
0.7×10^{-26} *e* cm
magnetic field origin

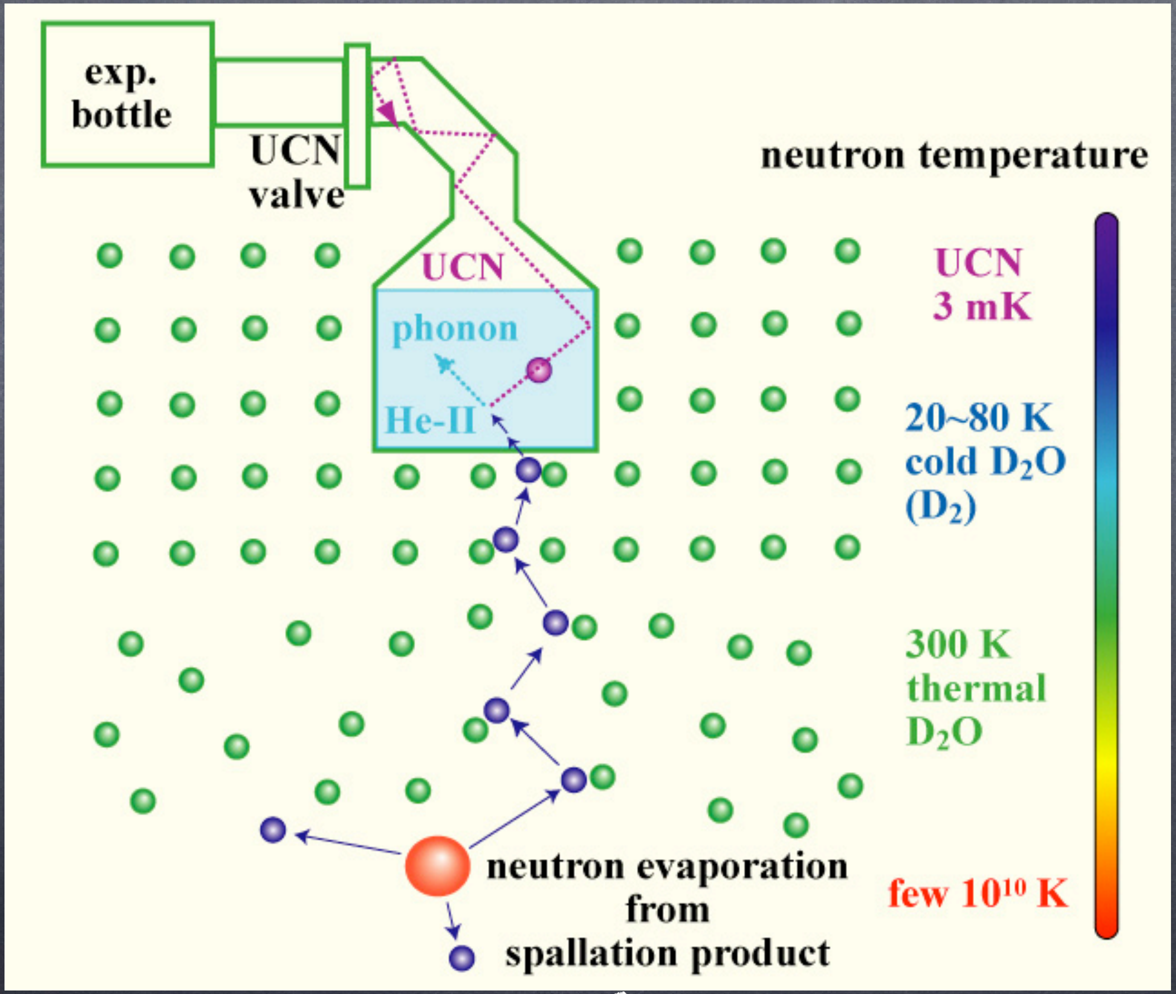


Statistical:
Spallation UCN production
in He-II

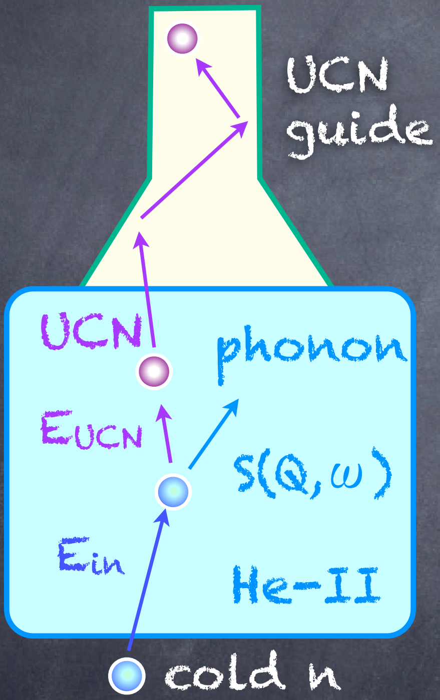
Systematic:
^{129}Xe magnetometer
to reduce
geometric phase effect

Our UCN production

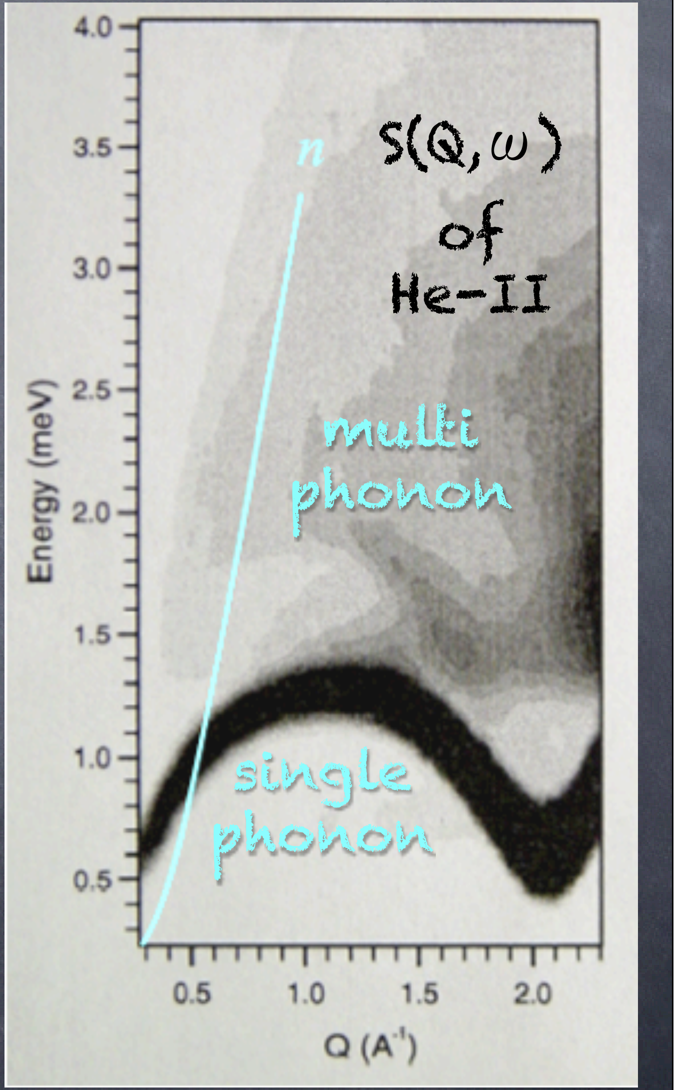
He-II is placed in a neutron source



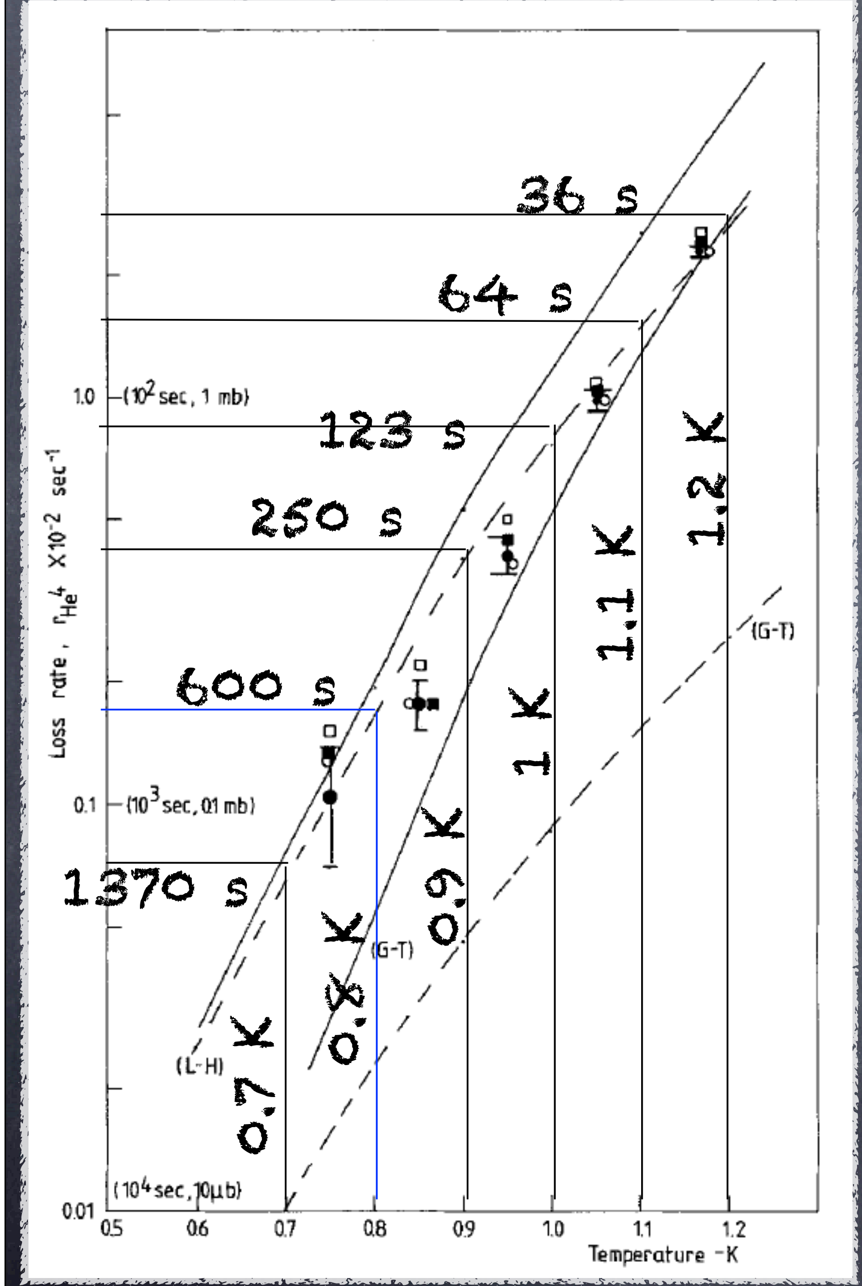
Super-thermal UCN production



We use phonon phase space for neutron cooling Golub and Pendlebury 1977



M.R. Gibbs et al. (1999)



UCN lifetime τ_s

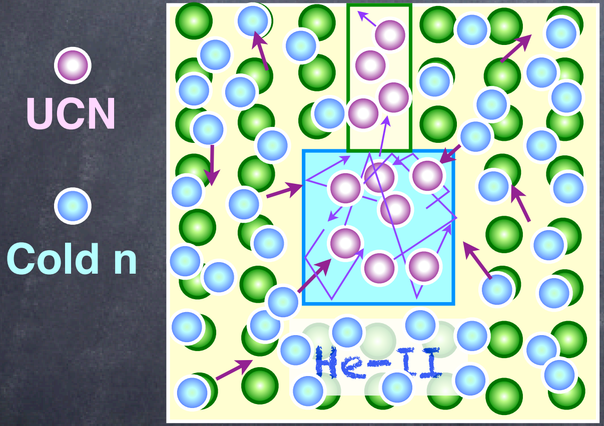
He-II [Golub et al. (1983)]
phonon up-scattering, $1/\tau_{ph} \propto T^7$

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

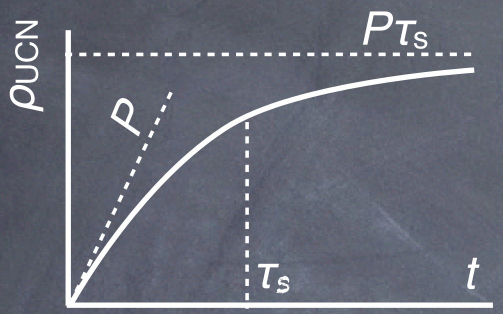
$\tau_s = 1/\{1/\tau_{ph} + 1/\tau_\beta + 1/\tau_w\}$
= 174 s

Superthermal UCN source

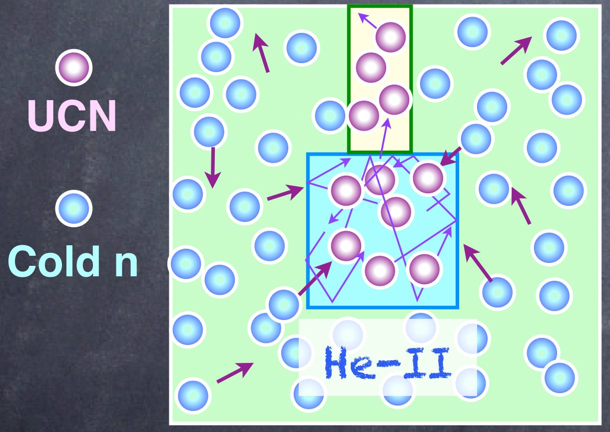


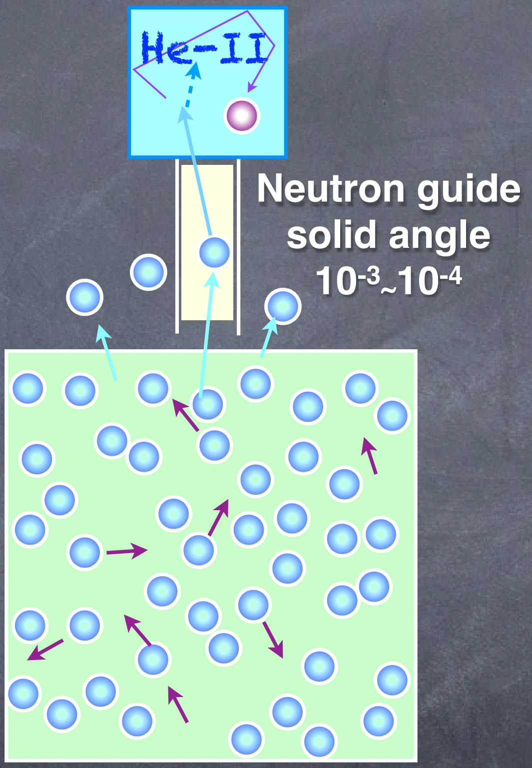
Cold source

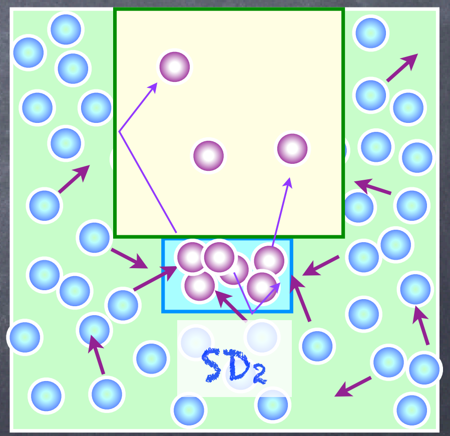
Superthermal UCN source



$$\rho_{UCN} = P \times \tau_s \times \varepsilon_d\text{(dilution factor)}$$

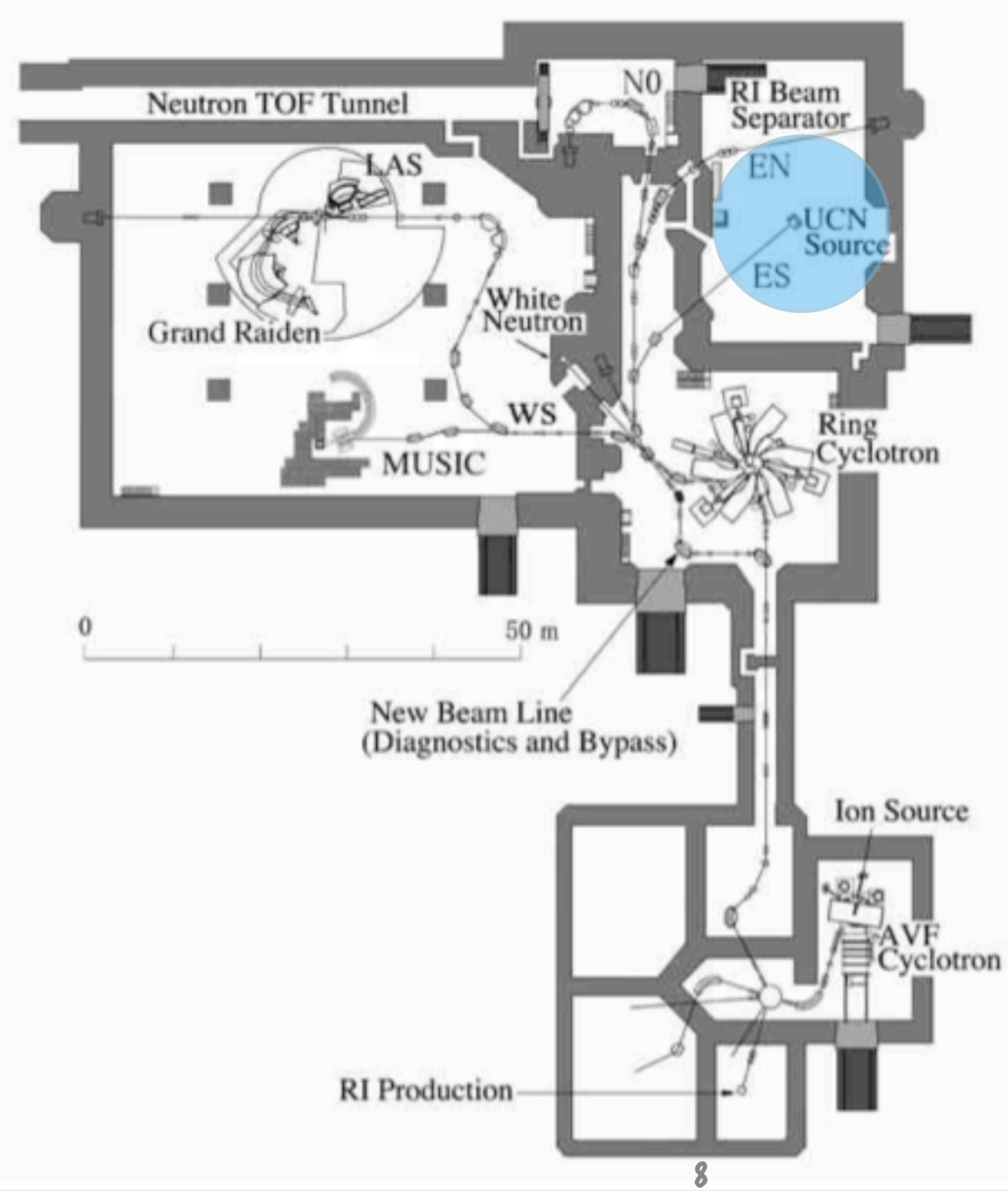






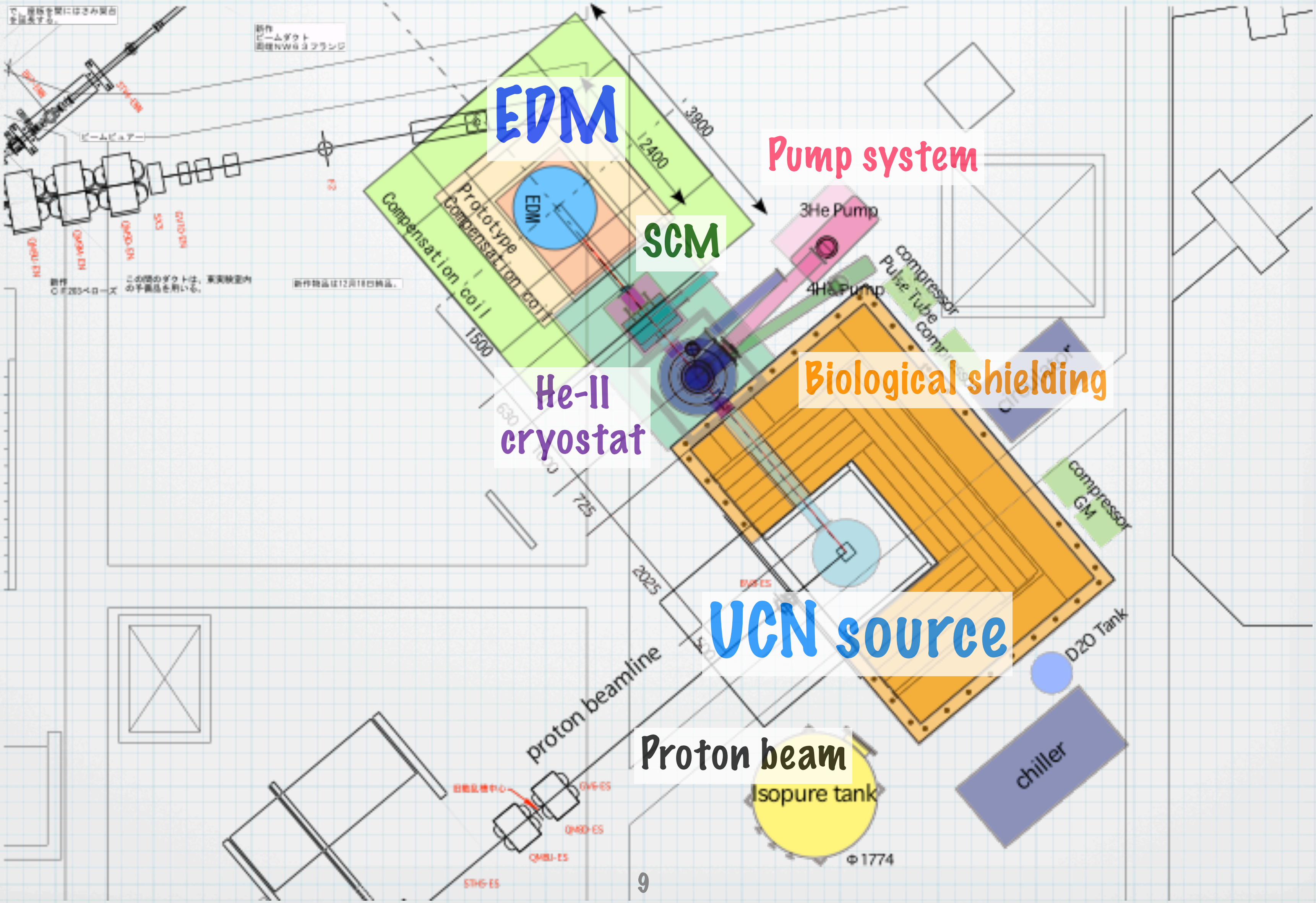
P	medium	small	large
$\tau_s(>t)$	long	long	short
ε_d	large (large prod. vol.)	large (large prod. vol.)	small (small prod. vol.)

UCN source at RCNP, Osaka

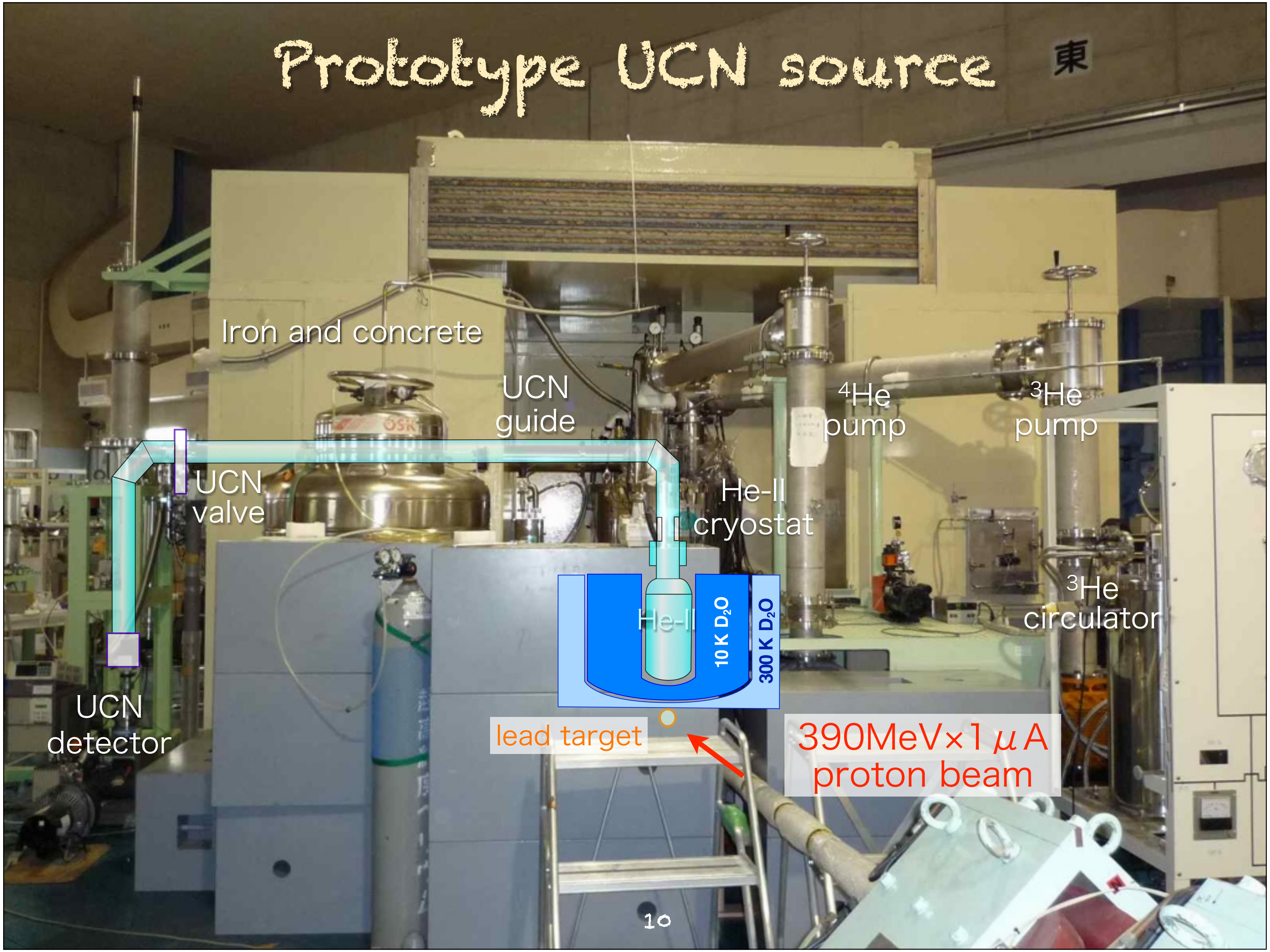


Ring Cyclotron

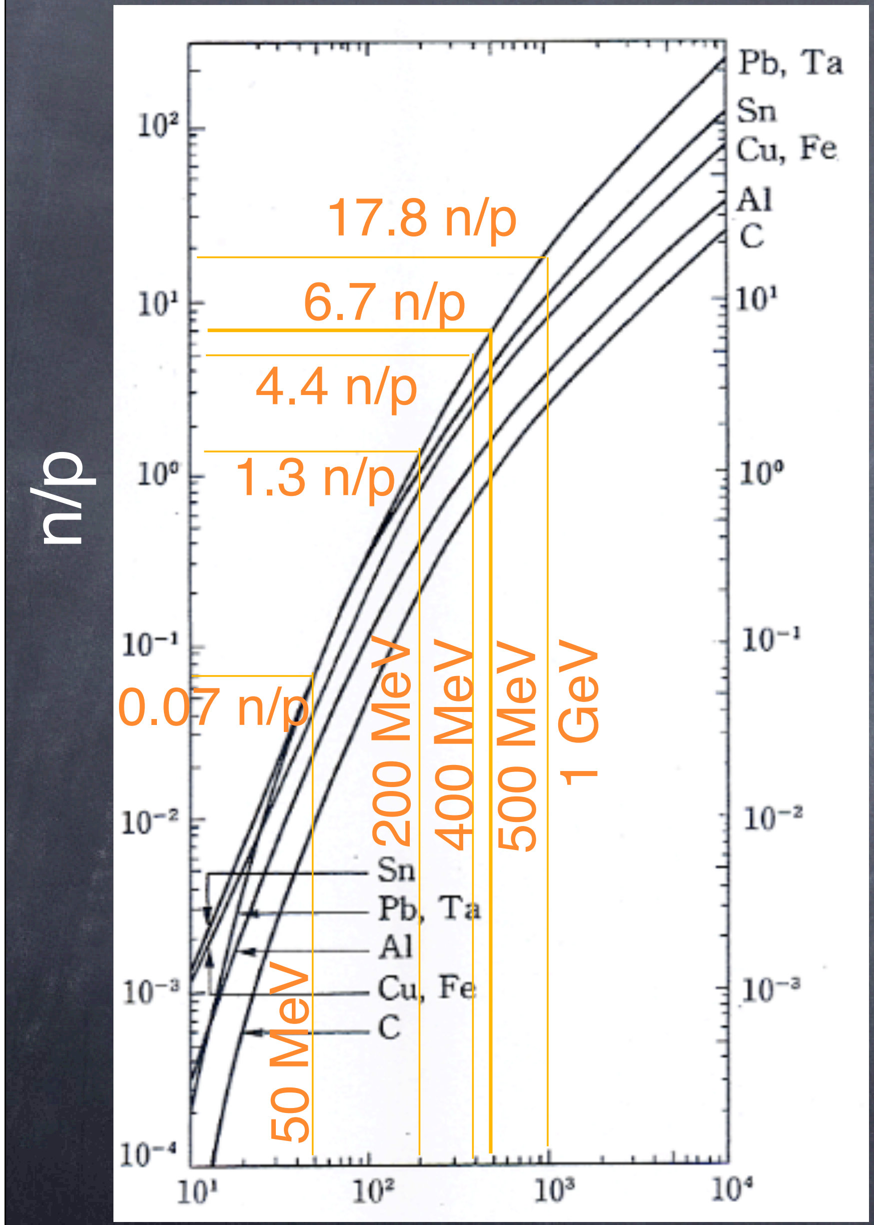
nEDM floor plan



Prototype UCN source

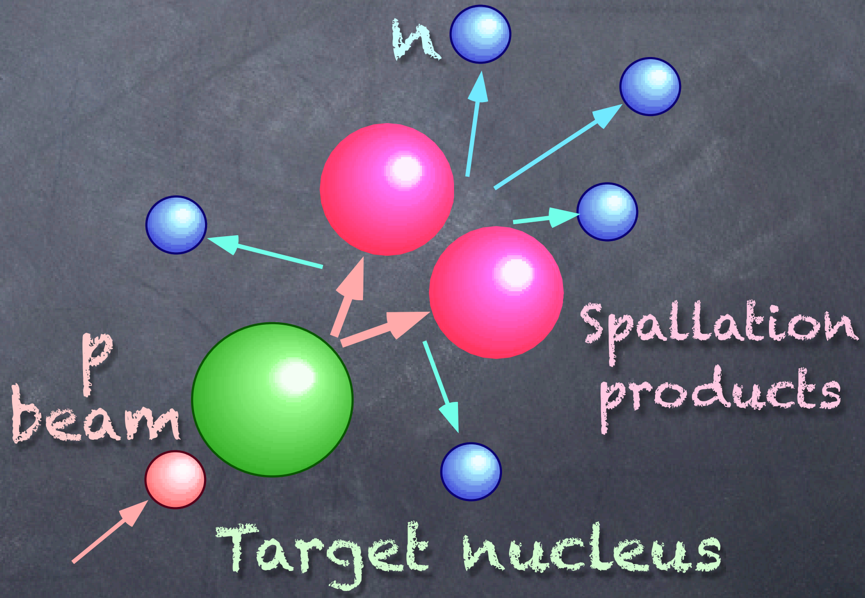


Spallation n production



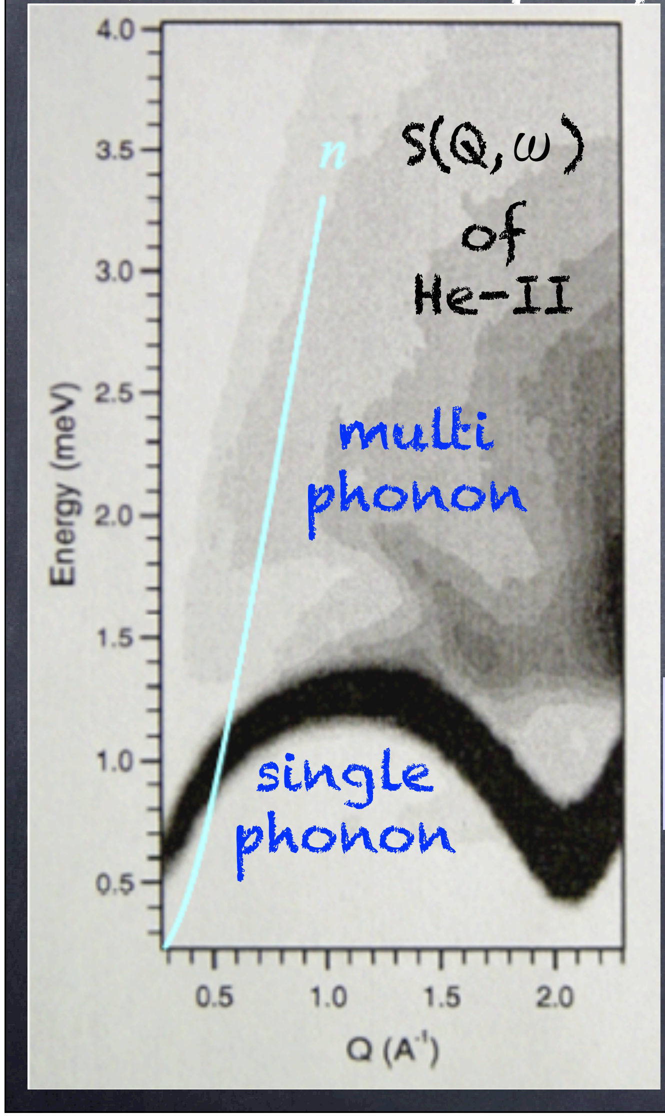
K. Tesch (1985)

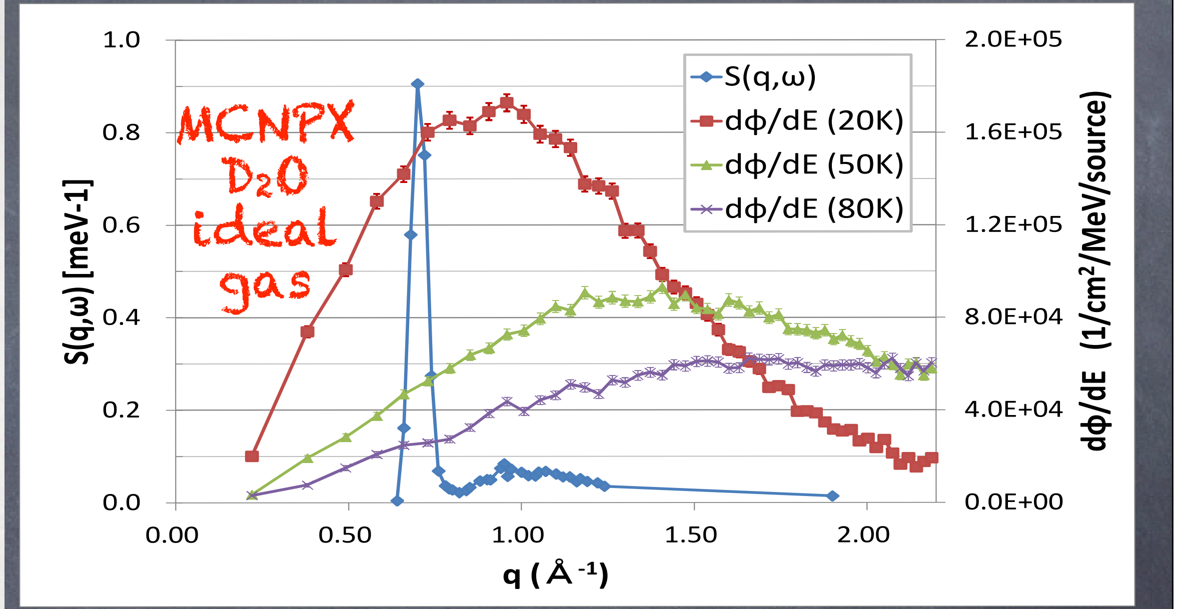
4.4 n/p at 400 MeV



Cold n for UCN production

M.R. Gibbs et al. (1999)





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

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

temperature in D₂O

UCN production at RCNP東

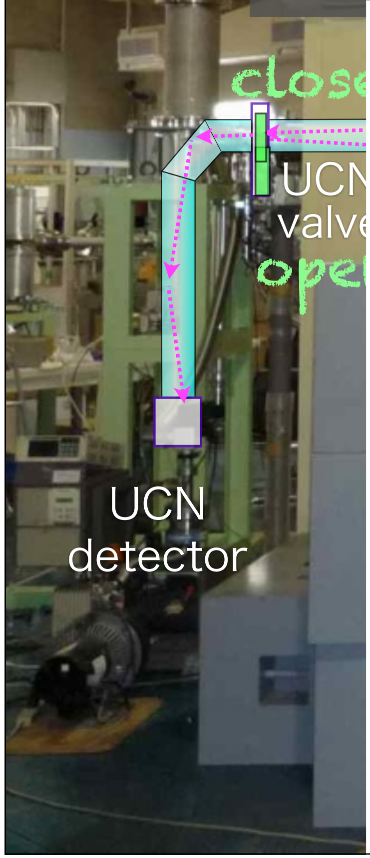
P = 4 UCN/cm³·s at E_c = 210 neV for 0.4 kW proton beam

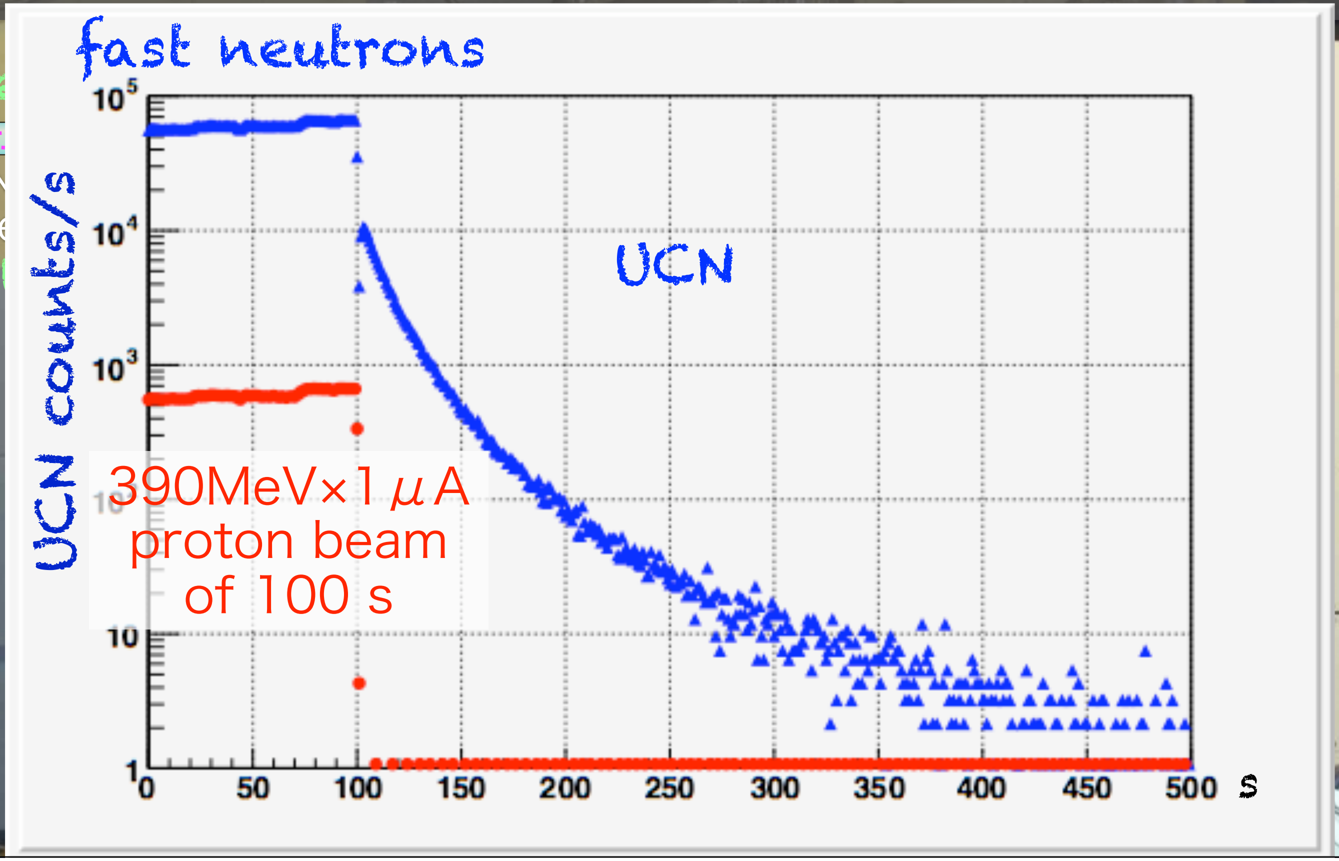
τ_s = 81 s Phys. Rev. Lett. 108(2012)134801

240 s irradiation

26 UCN/cm³ at E_c = 90 neV,

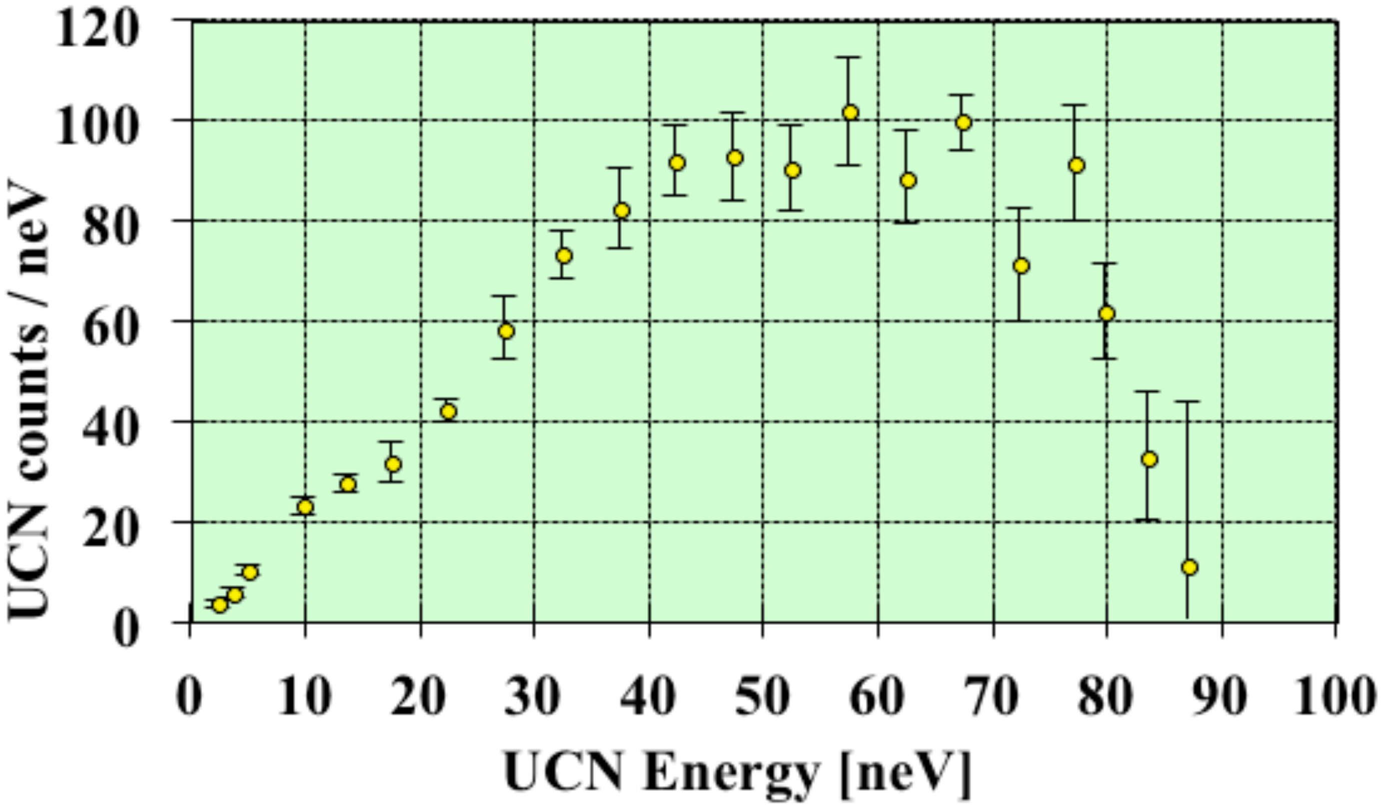
75 ($\propto E_c^{3/2}$) 180



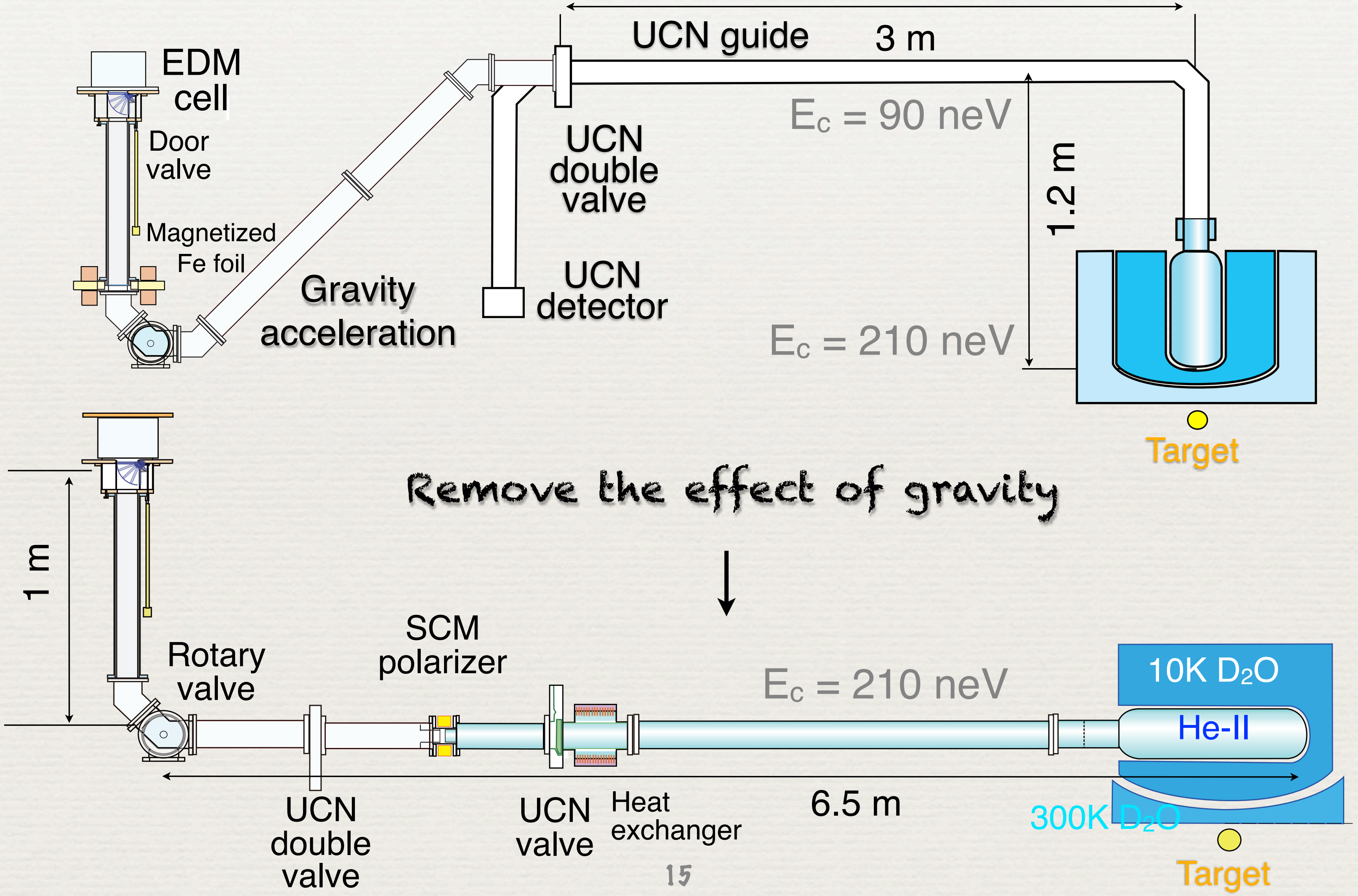


UCN energy spectrum

at the UCN valve



Improving UCN transport



Remove the effect of gravity

↓

Expected number of polarized UCN in the EDM cell

$$N = P\,\tau_s\,\varepsilon_d\,V$$

Vertical UCN source: P = 4 UCN/cm^3/s
26 UCN /cm^3 at E_c = 90 neV
Phys. Rev. Lett. 108(2012)134801

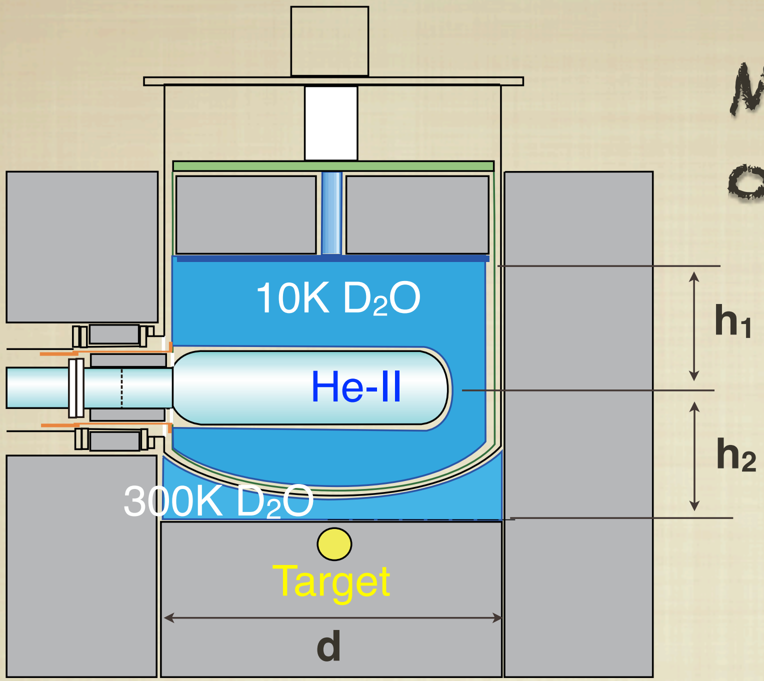
Horizontal:

Cold n flux in the new geometry	×1.2
RCNP p beam 10μA×400MeV	×10
TRIUMF p beam 40μA×500MeV	×5
Storage lifetime τ_s = 81 s → 150 s	×2
Dilution factor ε_d (volume ratio)	×6.0/9.9
UCN production volume	×1.4
After polarizer	×0.5

at RCNP N_{pol} = 260 UCN/cm^3 × 3L = 0.75×10^6

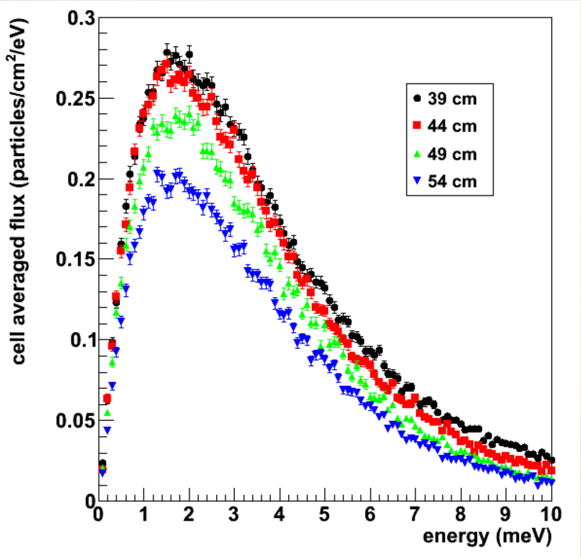
at TRIUMF N_{pol} = 1300 UCN/cm^3 × 3L = 3.8×10^6

Moderator reflector optimization by PHITS

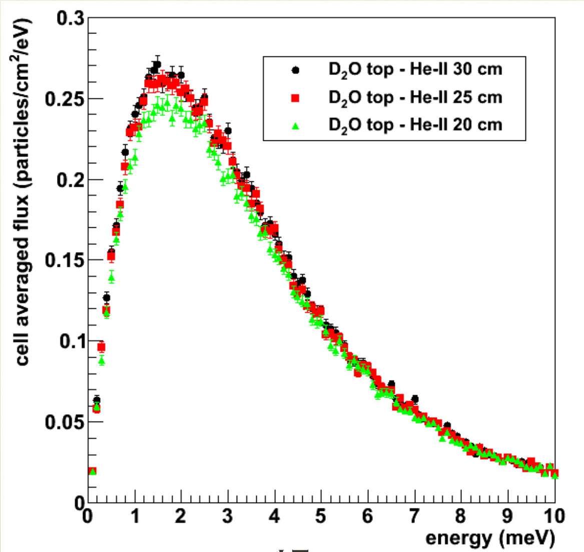


$h_1 = 44$ cm
$h_2 = 30$ cm
$d = 75$ cm

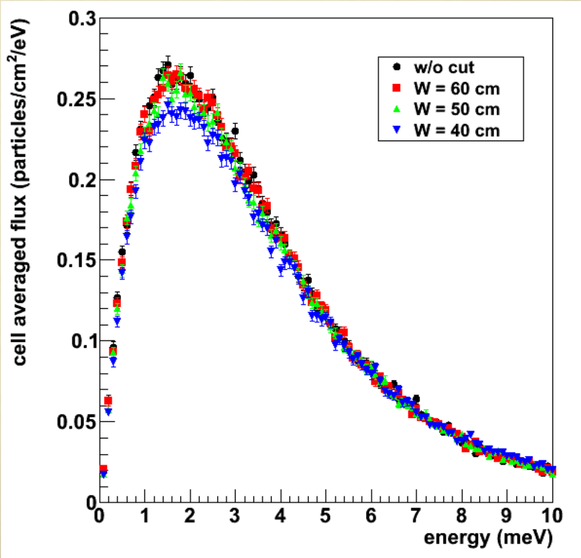
h_1



h_2

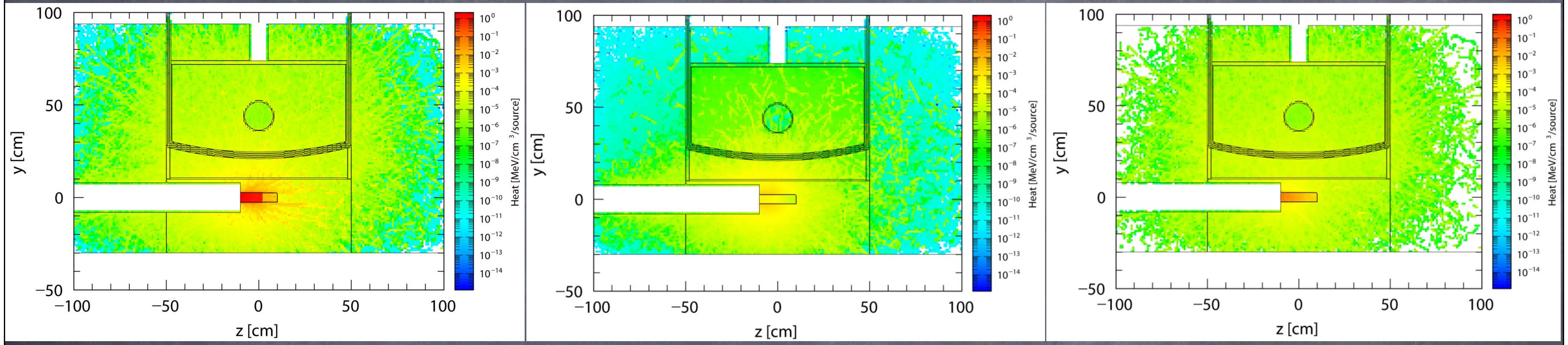


d



Energy deposit

PHITS code



Total Neutron photon

Heat deposit

He-II	20K D_2O	RCNP
0.1 W	4 W	400MeV×1μA
1 W	44 W	400MeV×10μA
		TRIUMF
5.2 W	266 W	500MeV×40μA

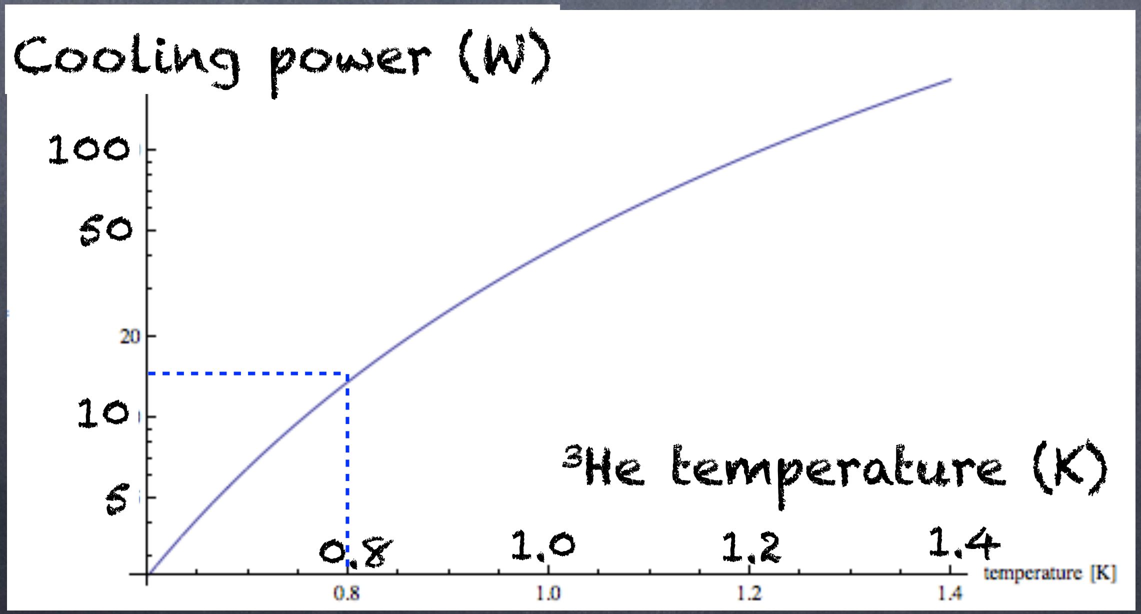
Removing γ heating in the He-II

γ heating : 5.2W (1W) in the He-II

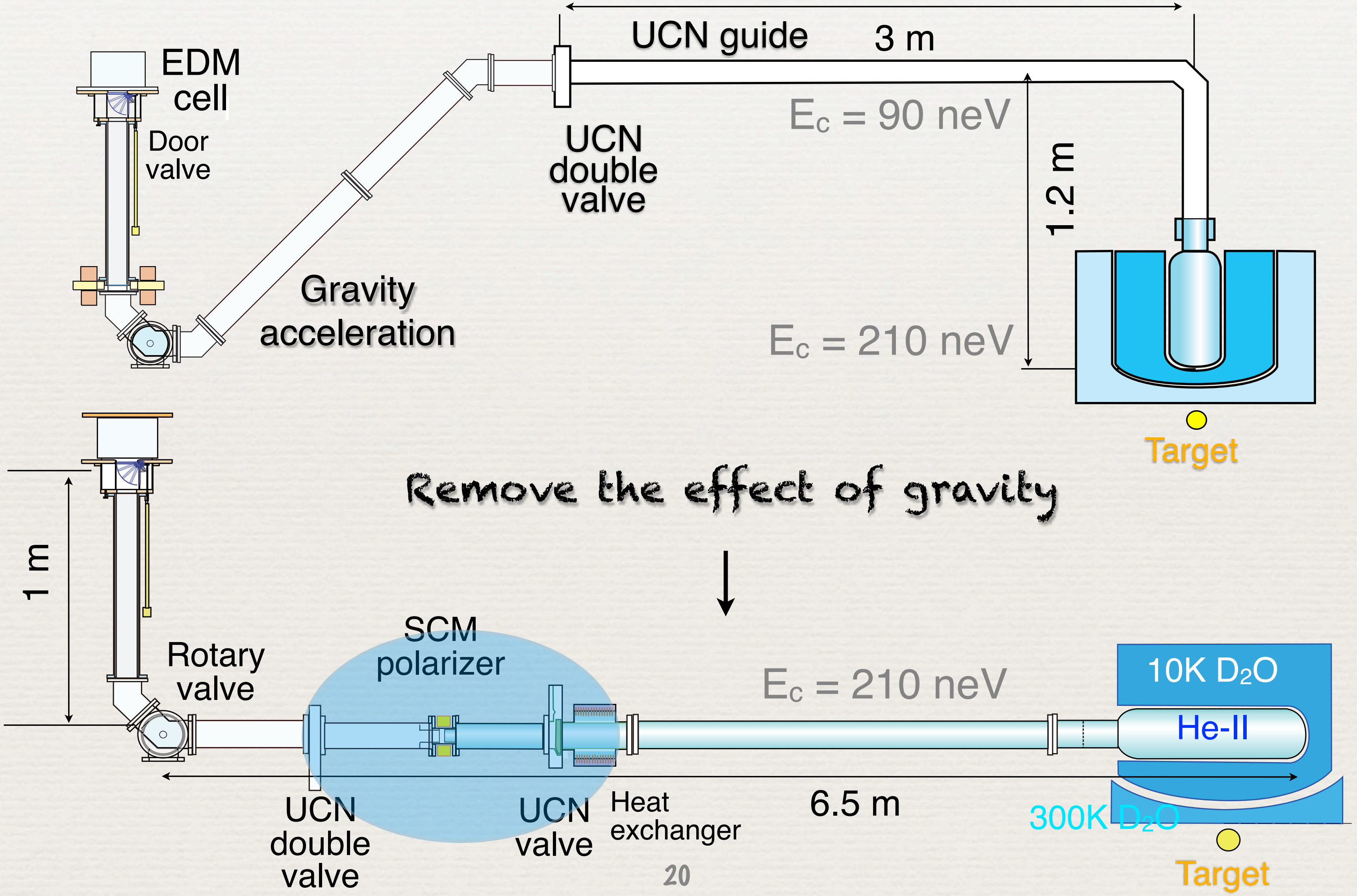
at a proton power of 20kW (4kW)

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



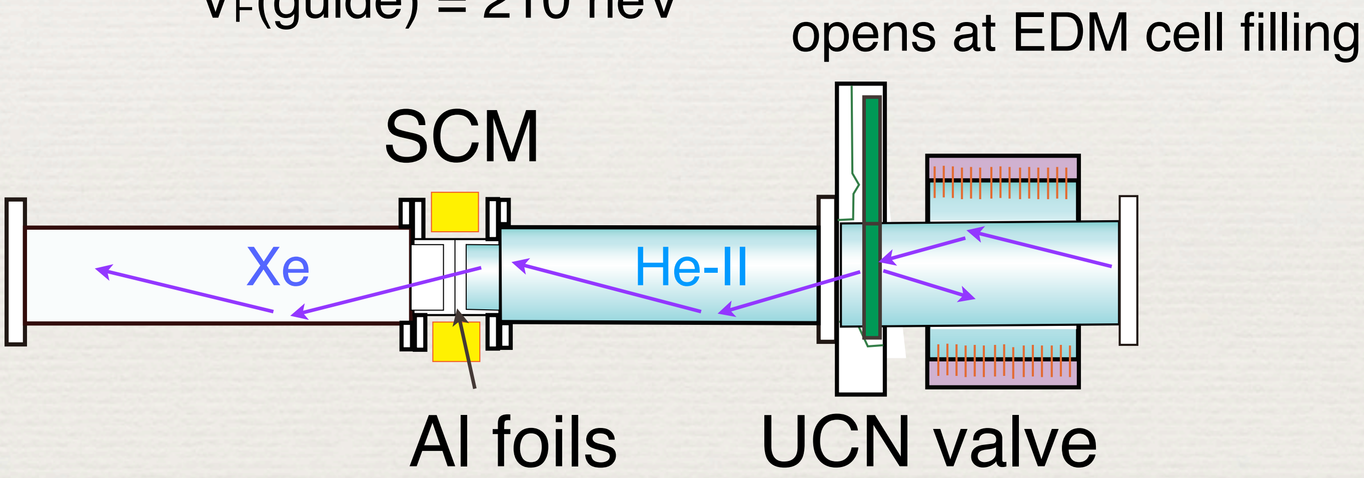
Cryogenic window



Remove the effect of gravity

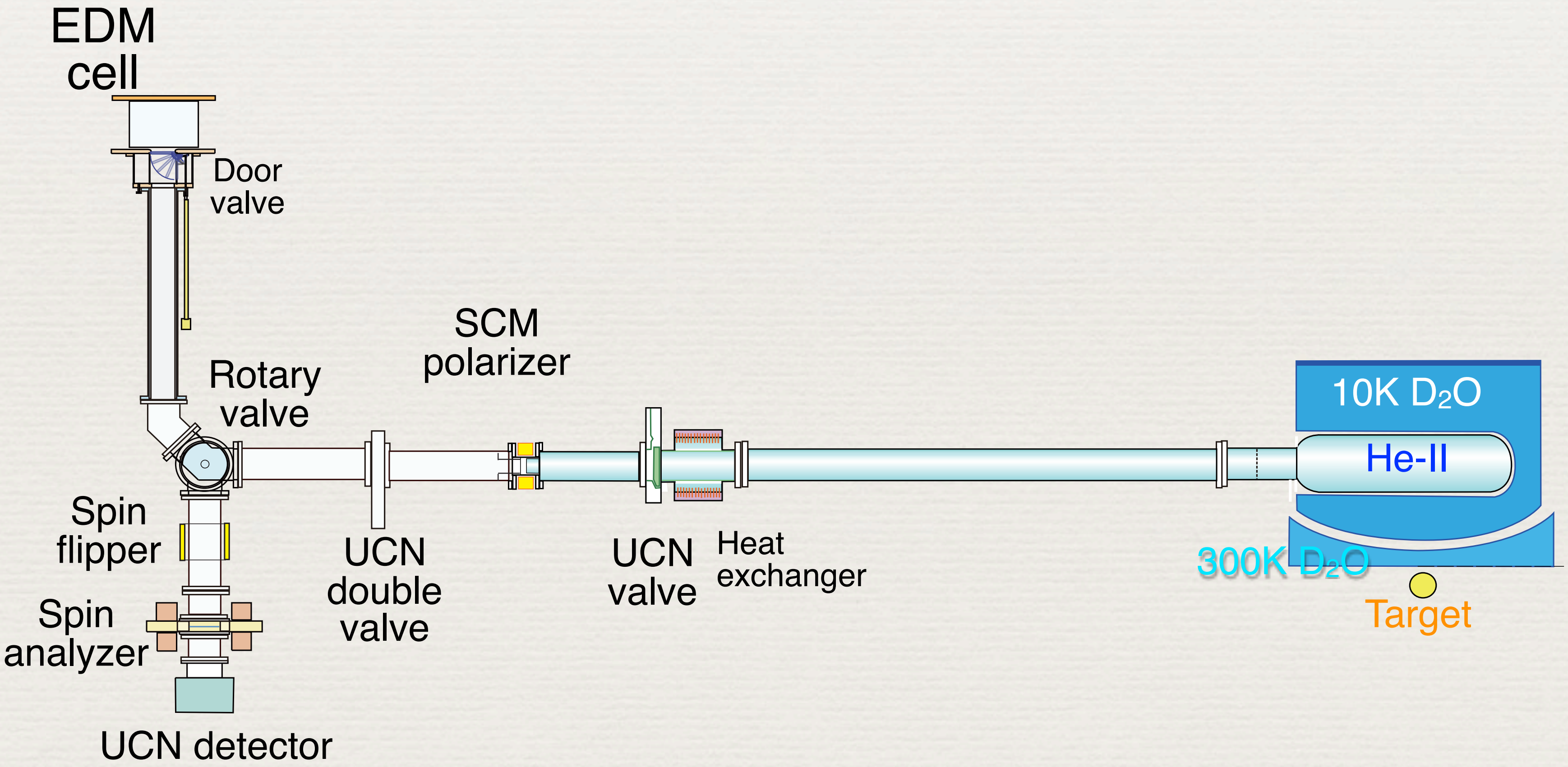
Extracting polarized UCN

μB(3.5T in SCM) = 210 neV
V_F(guide) = 210 neV

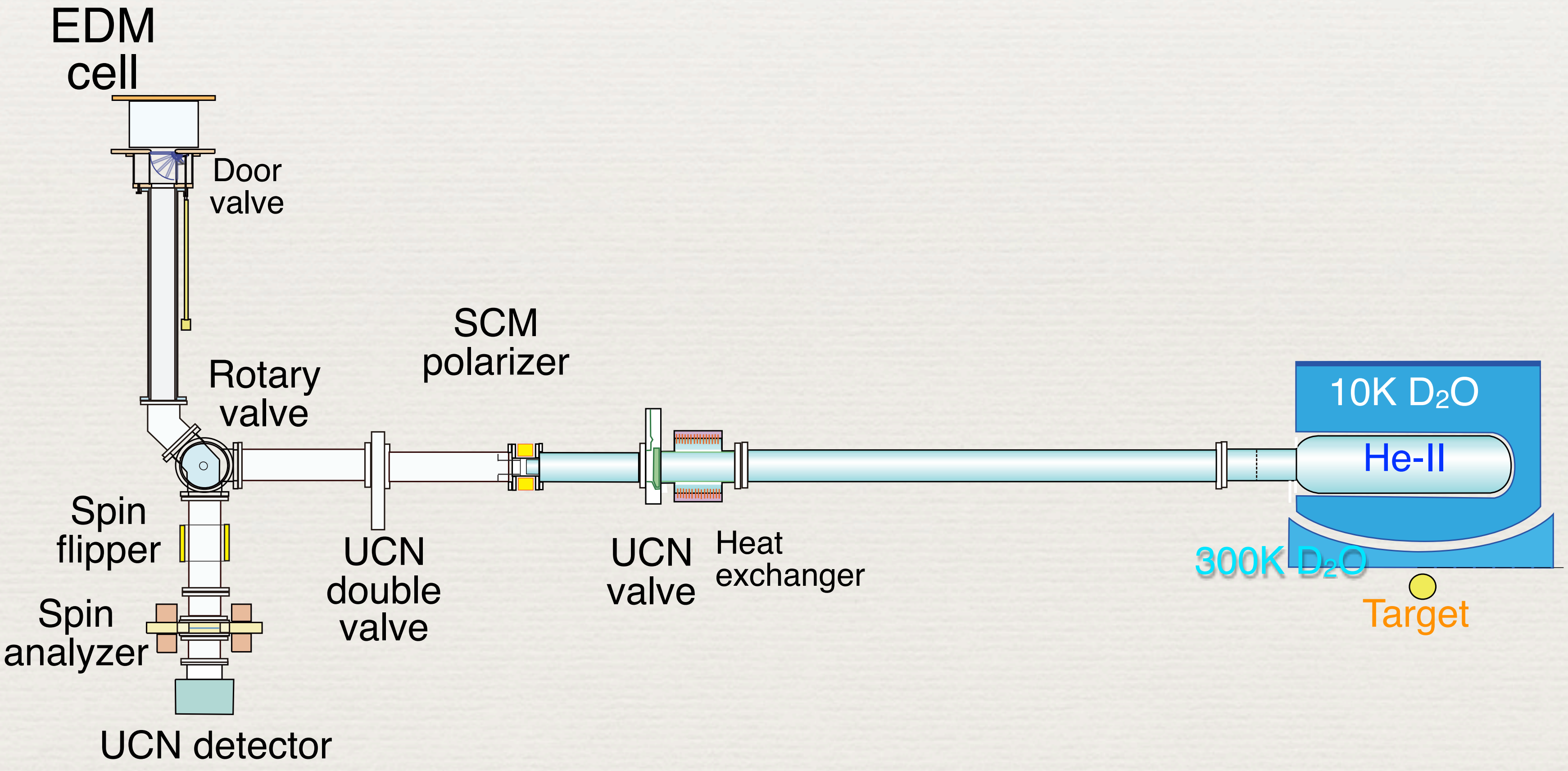


μB compensates V_F(Al) = 54 neV, and then enhances UCN transmission

UCN detector

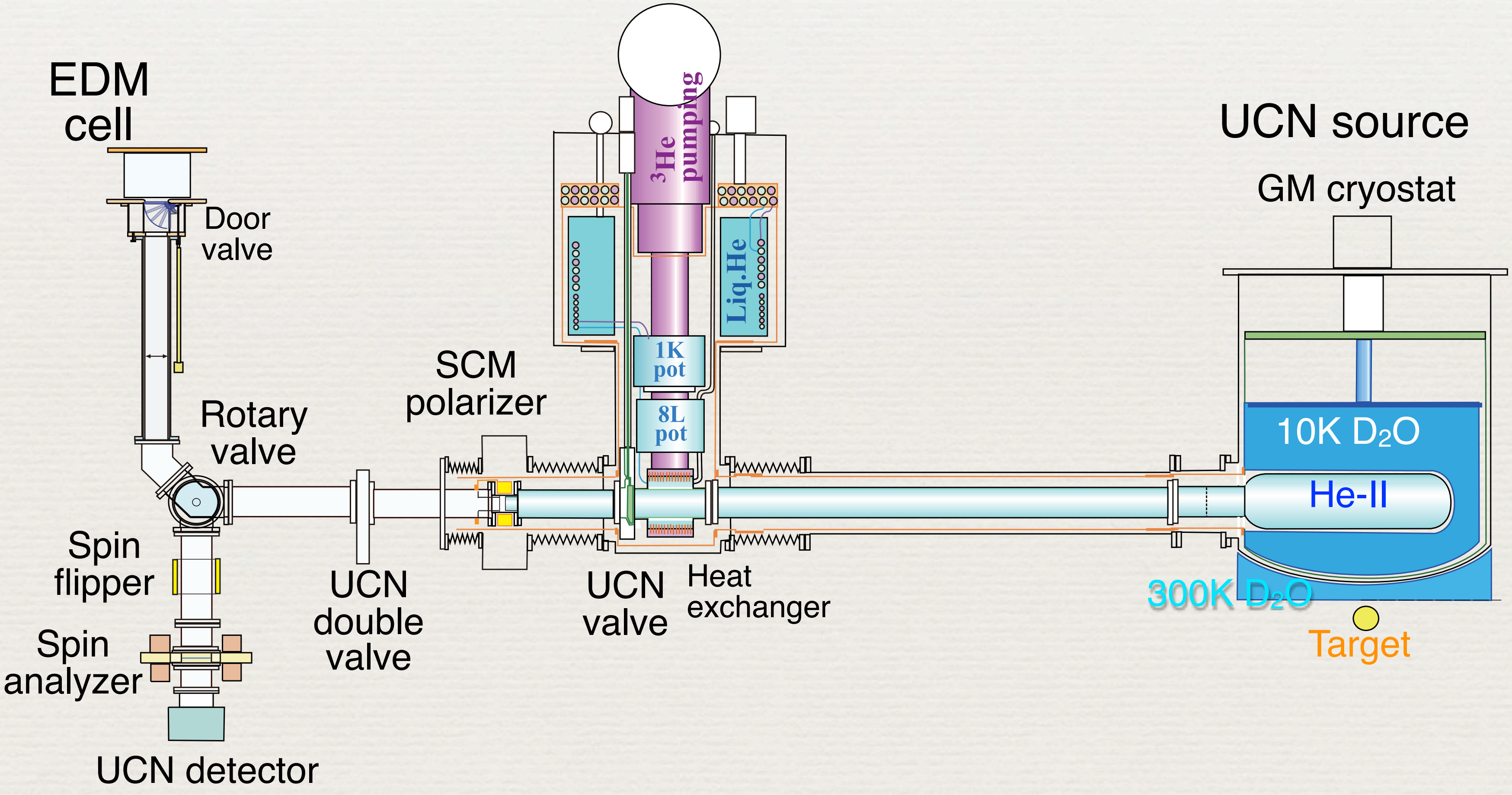


Rotary valve



Cryostat

He-II cryostat



EDM cell

Door valve

Rotary valve

Spin flipper

Spin analyzer

UCN detector

UCN double valve

SCM polarizer

UCN valve

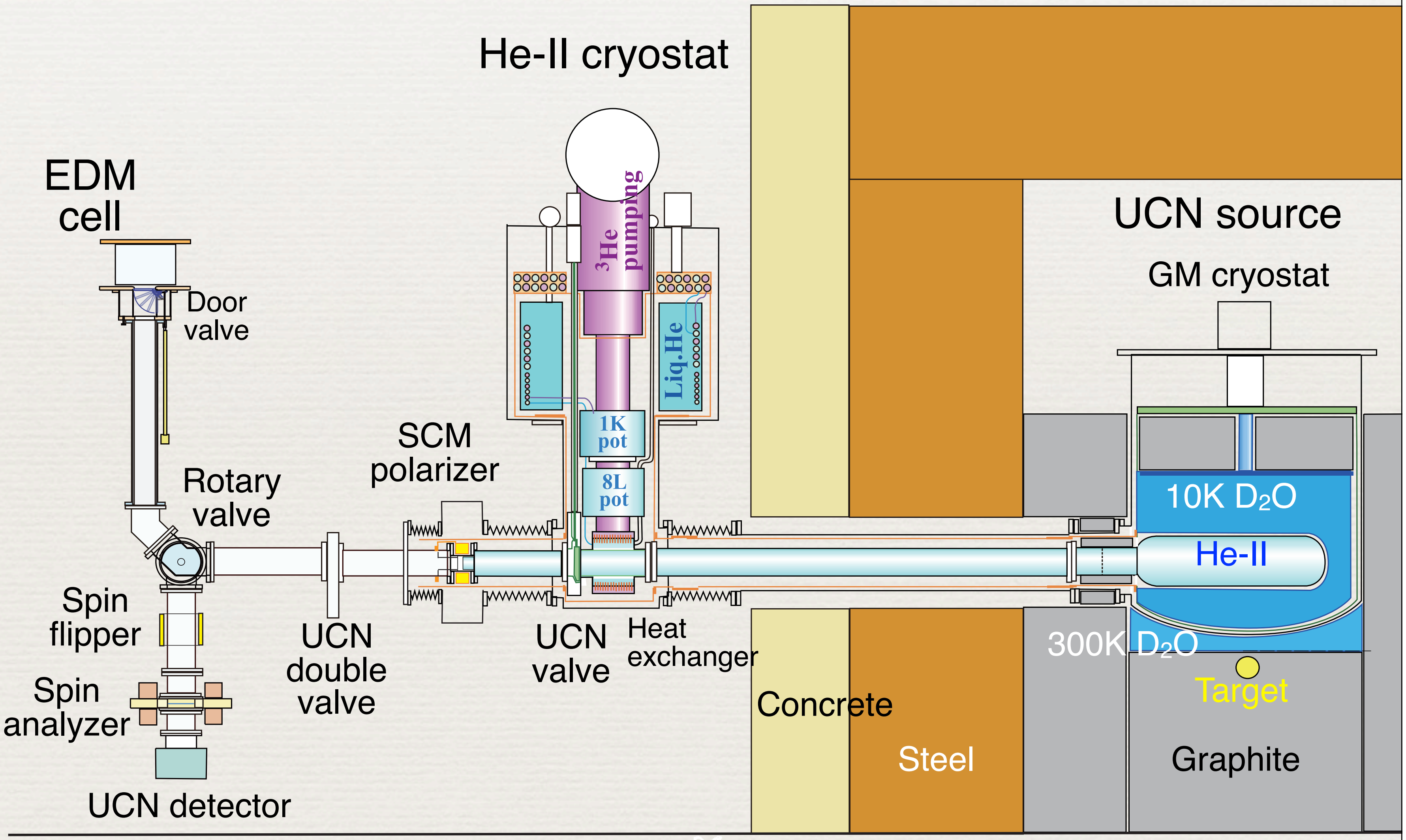
Heat exchanger

UCN source

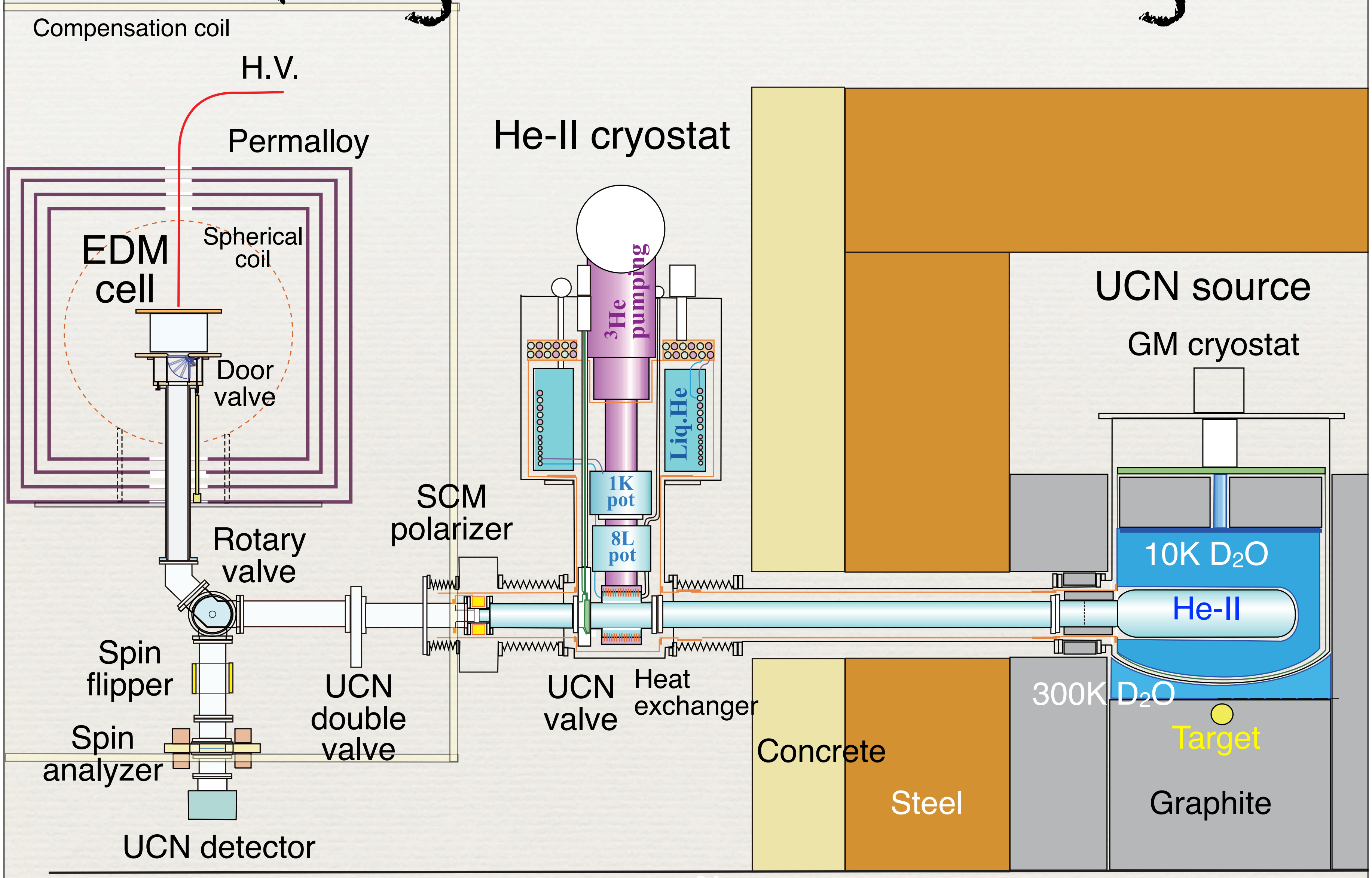
GM cryostat

Target

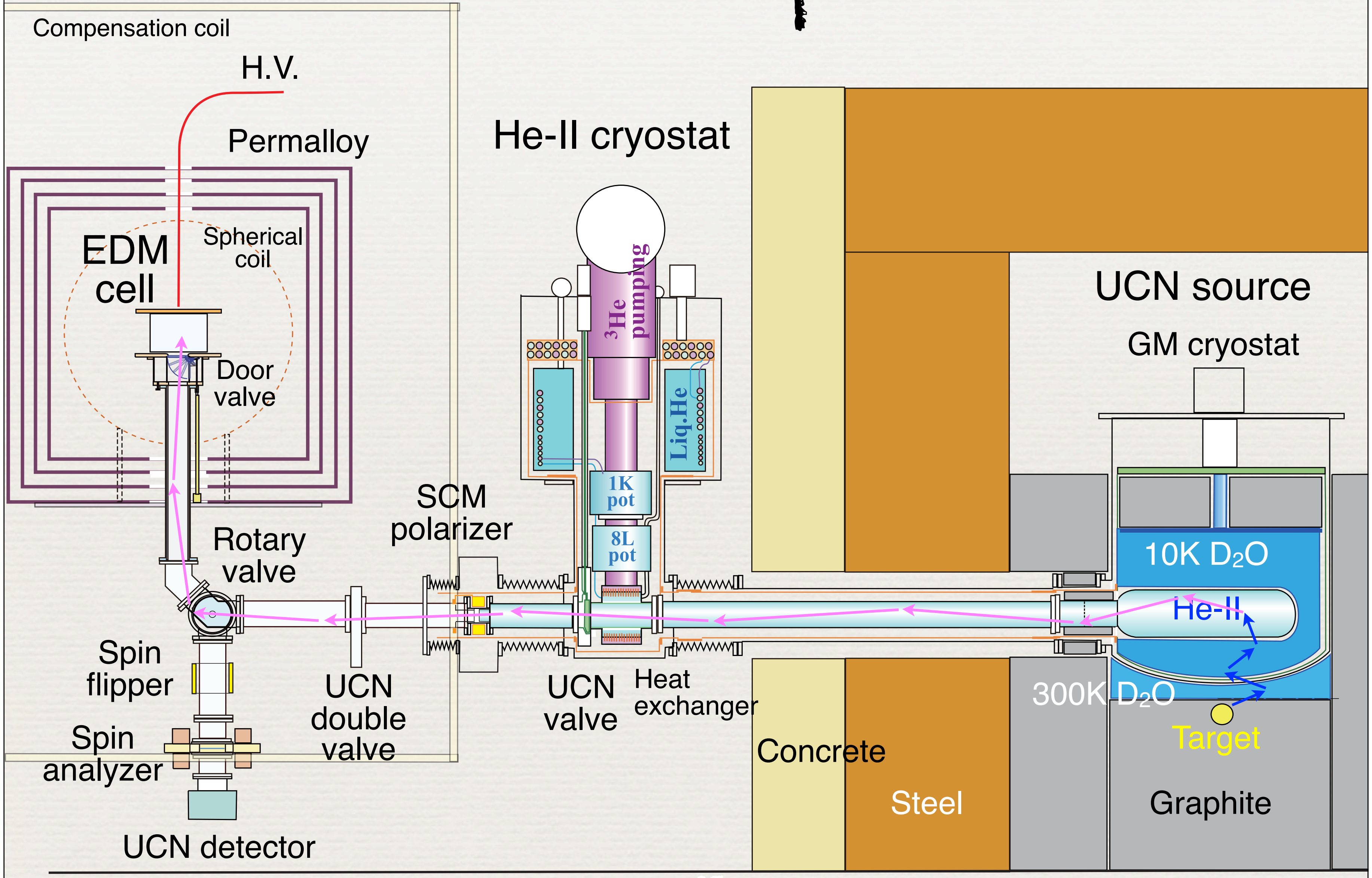
Reflector and shielding



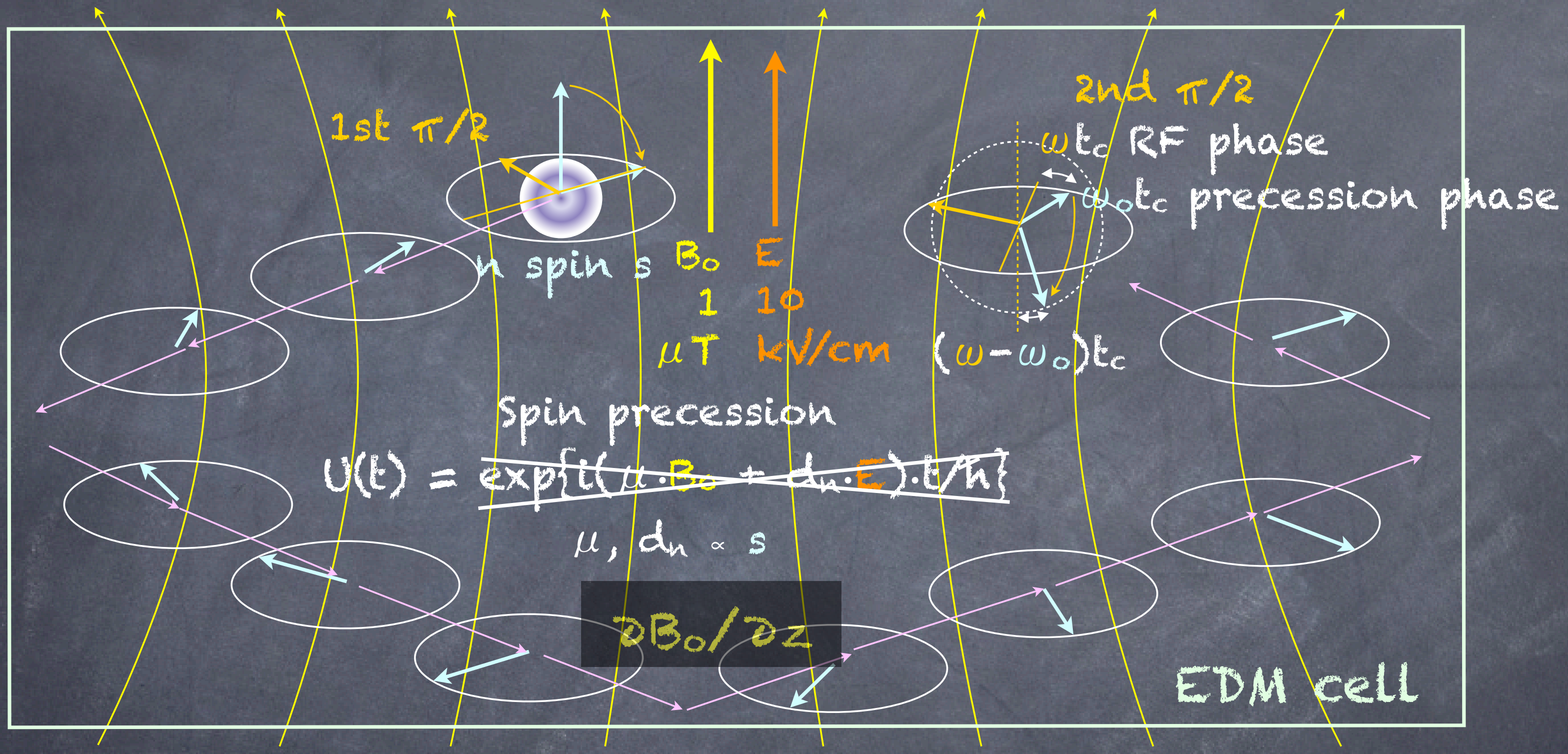
Magnetic shielding



Polarized UCN production



UCN spin precession



Spin precession

$$U(t) = \xcancel{\exp\{i(\mu\cdot B_0 + d_n\cdot E)\cdot t/\hbar\}}$$

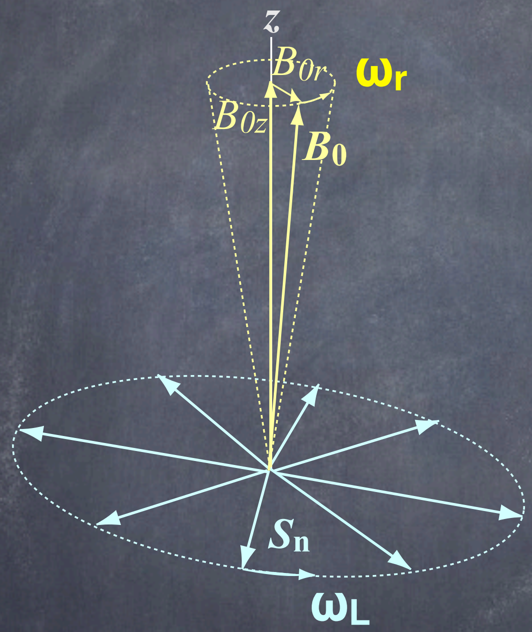
$$\mu,\ d_n \propto s$$

Geometric phases arise from the rotation of the transverse fields, $(\partial B_0/\partial z)r/2$ and $E\times v/c^2$

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

Effect of time dependent interaction

Phys.Lett. A376(2012)1347



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

$$V(t) = -\boldsymbol{\mu}\cdot\boldsymbol{B}_{xy}(t)$$

$$= -\gamma \boldsymbol{s}\cdot\left\{\boldsymbol{E}\times\boldsymbol{v}(\boldsymbol{t})/c^2 - (\partial B_{0z}/\partial z)\,\boldsymbol{r}(t)/2\right\}$$

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

$$+\left(\frac{-i}{\hbar}\right)^2 \int_0^t dt' \int_0^{t'} dt'' V_I(t') V_I(t'') + \cdots$$

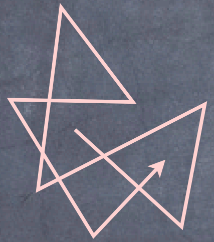
$$V_I(t) = e^{iH_0 t/\hbar}\{-\boldsymbol{\mu}\cdot\boldsymbol{B}_{xy}(t)\}e^{-iH_0 t/\hbar}$$

$E\times v/c^2 \cdot (\partial B_0/\partial z) r/2$ cross terms induce false effect

Increase ^{129}Xe atomic number density so that mean free path λ becomes small

GPE

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



r(t) almost constant for short mean free path λ

v(t-τ) rapidly changes

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

Diffusion velocity is in the adiabatic regime $\omega_r \ll \omega_L$

Suppression factor $[\{v_{xy}\lambda/(2R)^2\}/(\omega_0/2\pi)]^2 = (\pi v_{xy}\lambda/2R^2\omega_0)^2$

$(v_{xy}/c/\underline{B_{0z}})^2$

$v_{xy}\lambda/(2R)^2 = 196\,\mathrm{m/s}\times 5\times 10^{-3}\,\mathrm{m}/0.5^2\,\mathrm{m}^2 = 4\,\mathrm{Hz} \ll \omega_0/2\pi = 300\,\mathrm{Hz}$

at R = 25 cm, $\partial B_{0z}/\partial z = 1\,\mathrm{nT/m}$, $B_{0z} = 10\,\mu\mathrm{T}$

$d_{afXen} \to 3\times 10^{-28}$ e·cm at 3 mTorr

$\to 1\times 10^{-28}$ e·cm at 5 mTorr, 6 cm E gap

Time line

2012	at RCNP	400MeV×1μA,	$\rho \equiv$ 26 UCN/cm^3	
2014	at RCNP	400MeV×10μA,	ρ_{pol} = 260 UCN/cm^3	10^{-26}~10^{-27} *e* cm
2016 ~	at TRIUMF	500MeV×40μA,	1300 UCN/cm^3	10^{-27}~10^{-28} *e* cm

We are waiting for helium

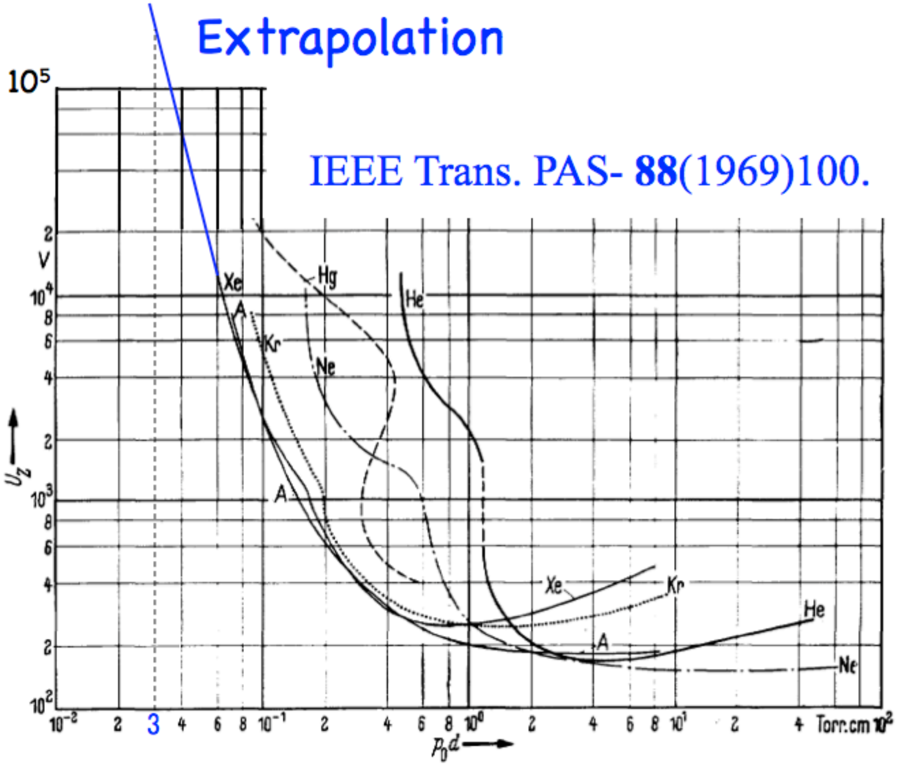
Cooling test achieved 1.2K

Thanks

HV break down

with ^{129}Xe gas

Extrapolation

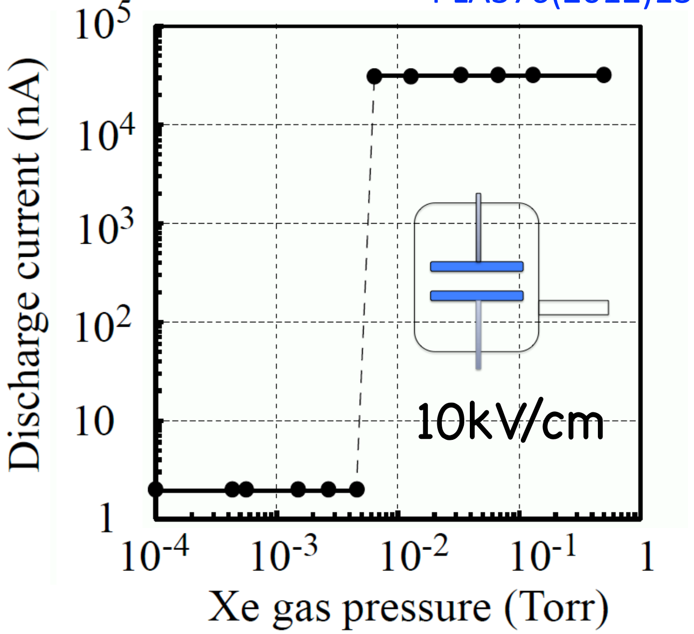


IEEE Trans. PAS- **88**(1969)100.

Fig. 7. Breakdown characteristics of the noble gases. Hg characteristic from [13].

Our data

PLA376(2012)1347



10kV/cm