A new ultracold neutron production for neutron confinement

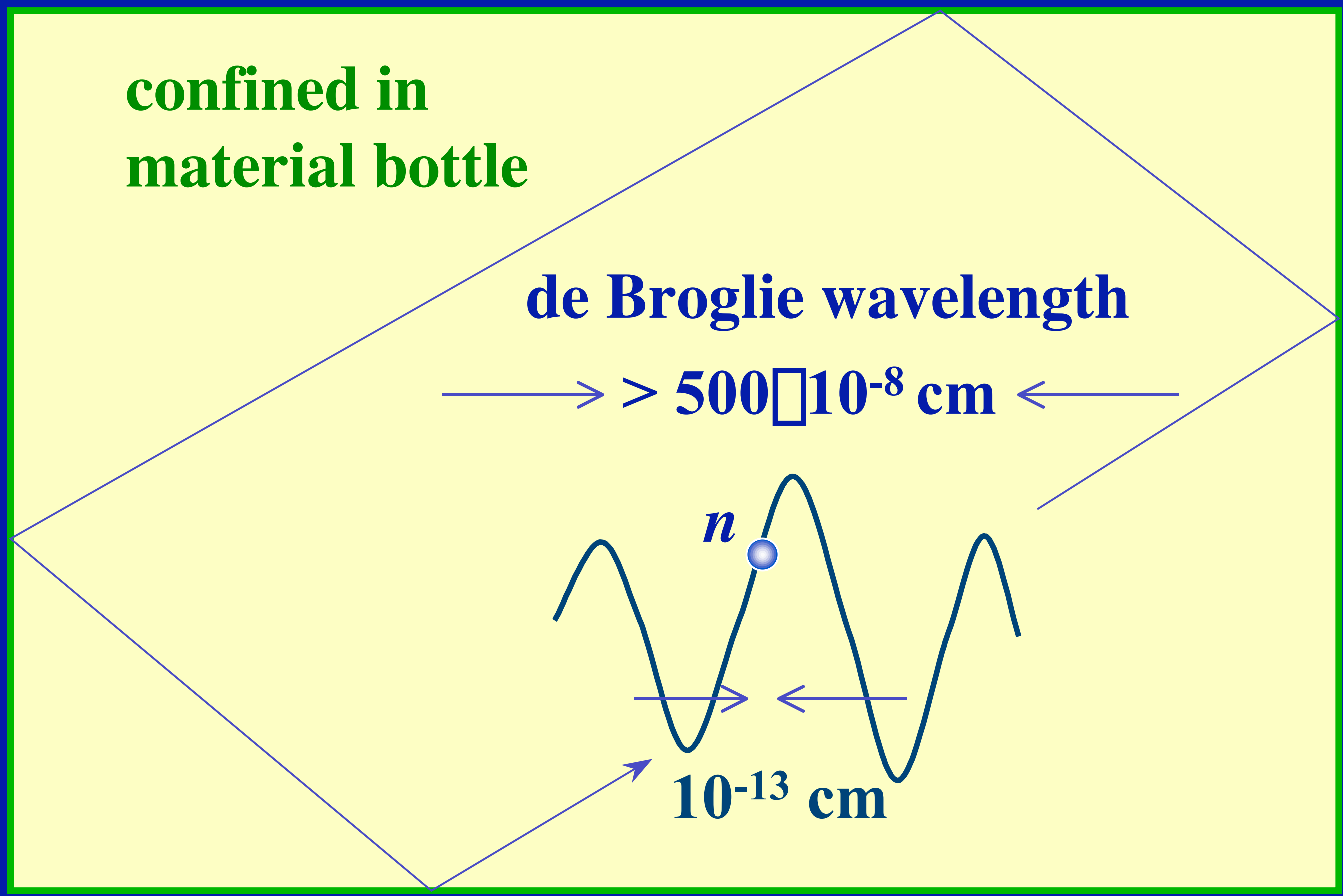
KEK physics seminar, Jan. 28, 2003

Y. Masuda (IPNS, KEK)

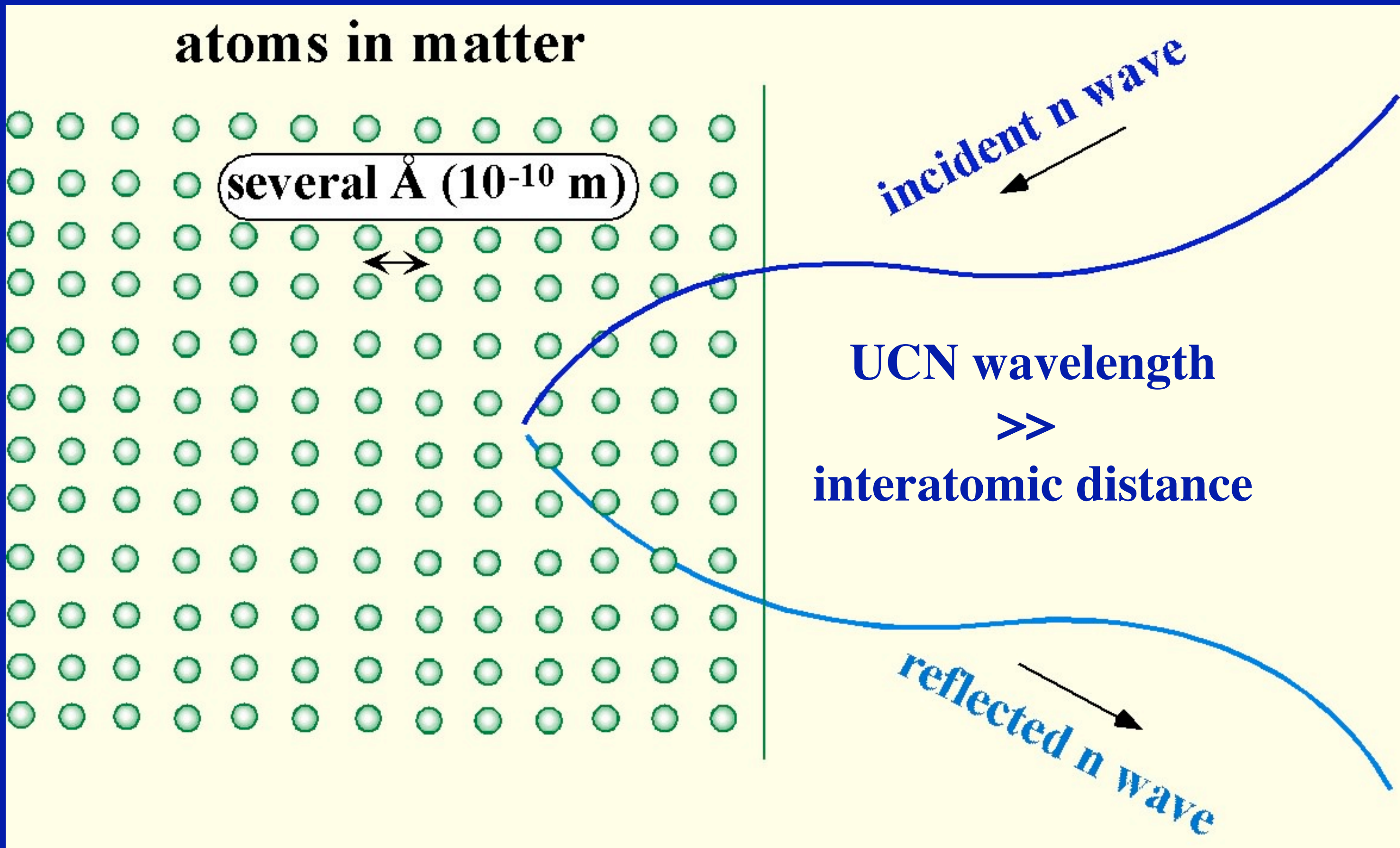
1. confinement of neutron wave
2. physics with UCN
3. a new generation UCN source

Ultra cold neutrons (UCN)

very low energy neutrons



reflection of neutron wave

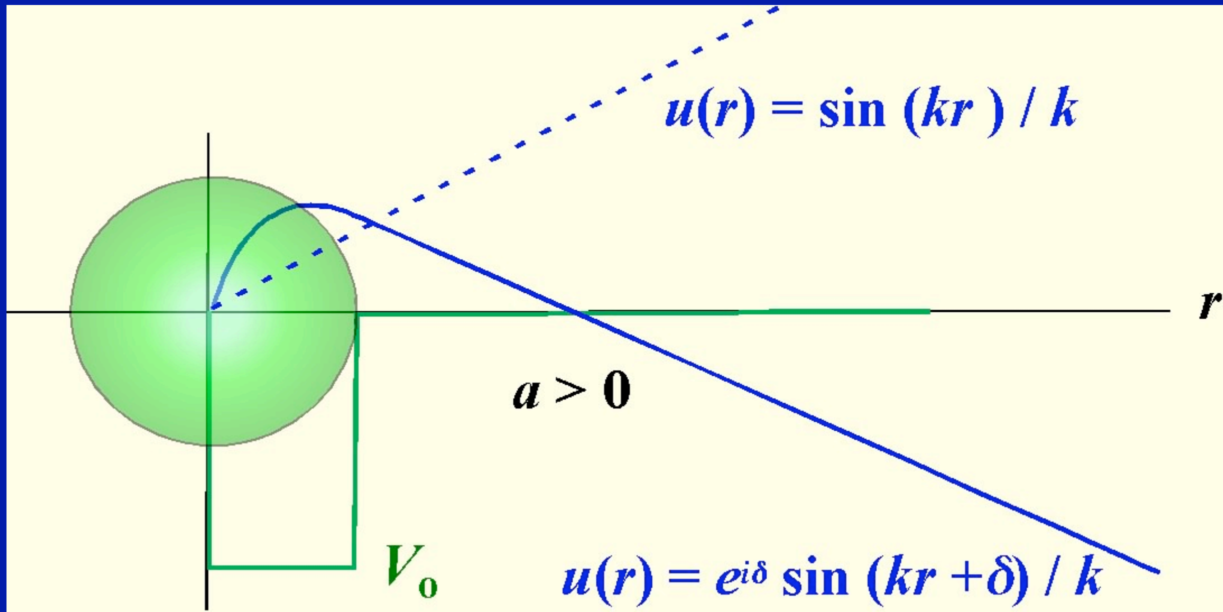


potential for neutron wave: $2\pi\hbar^2/m \ \sum a_i \ \delta(r - r_i)$

$E_c \ = 2\pi\hbar^2/m \ Na$

Fermi potential of the nucleus

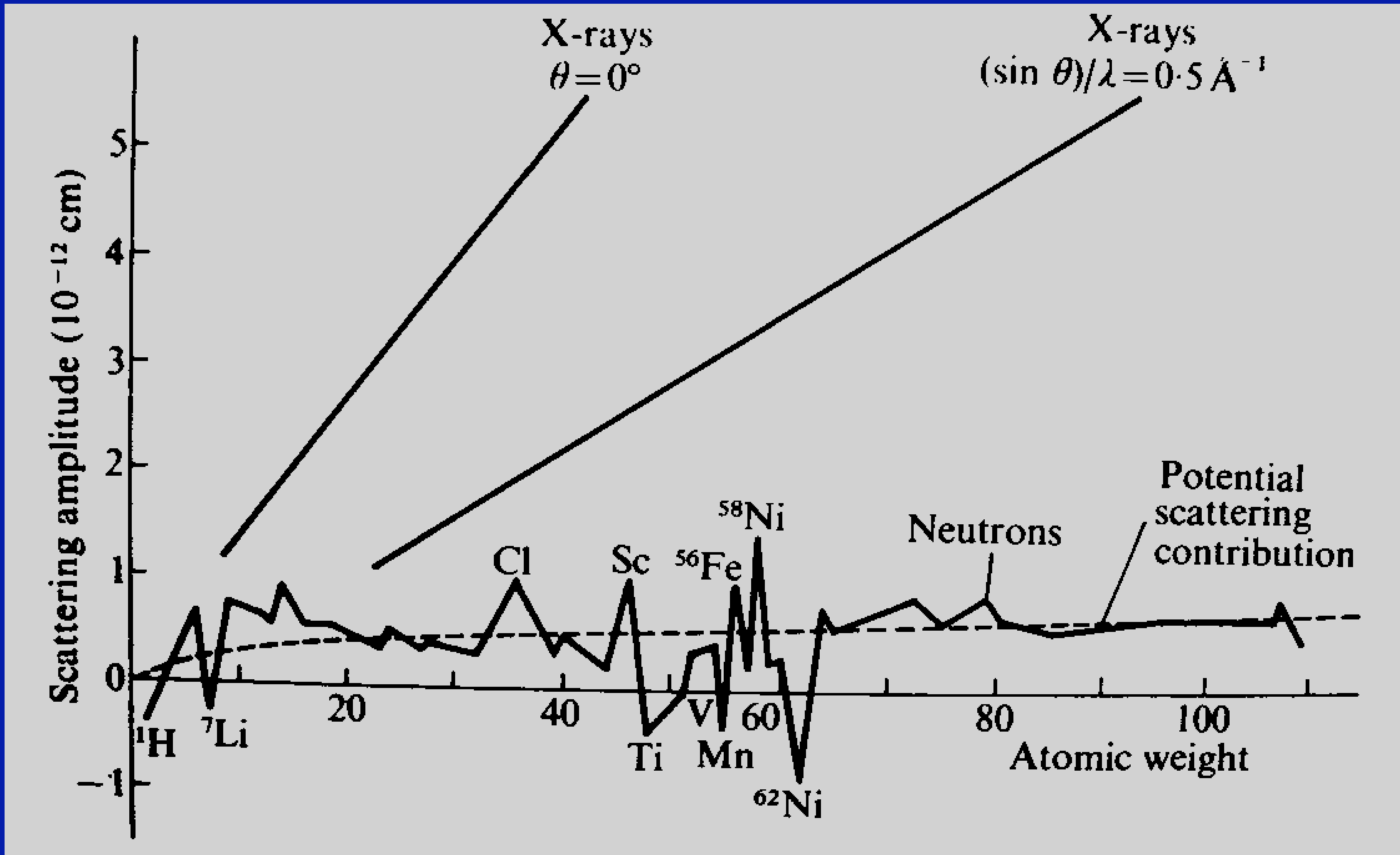
attractive nuclear force distorts the neutron wave, reverses the phase, and repels the neutron wave



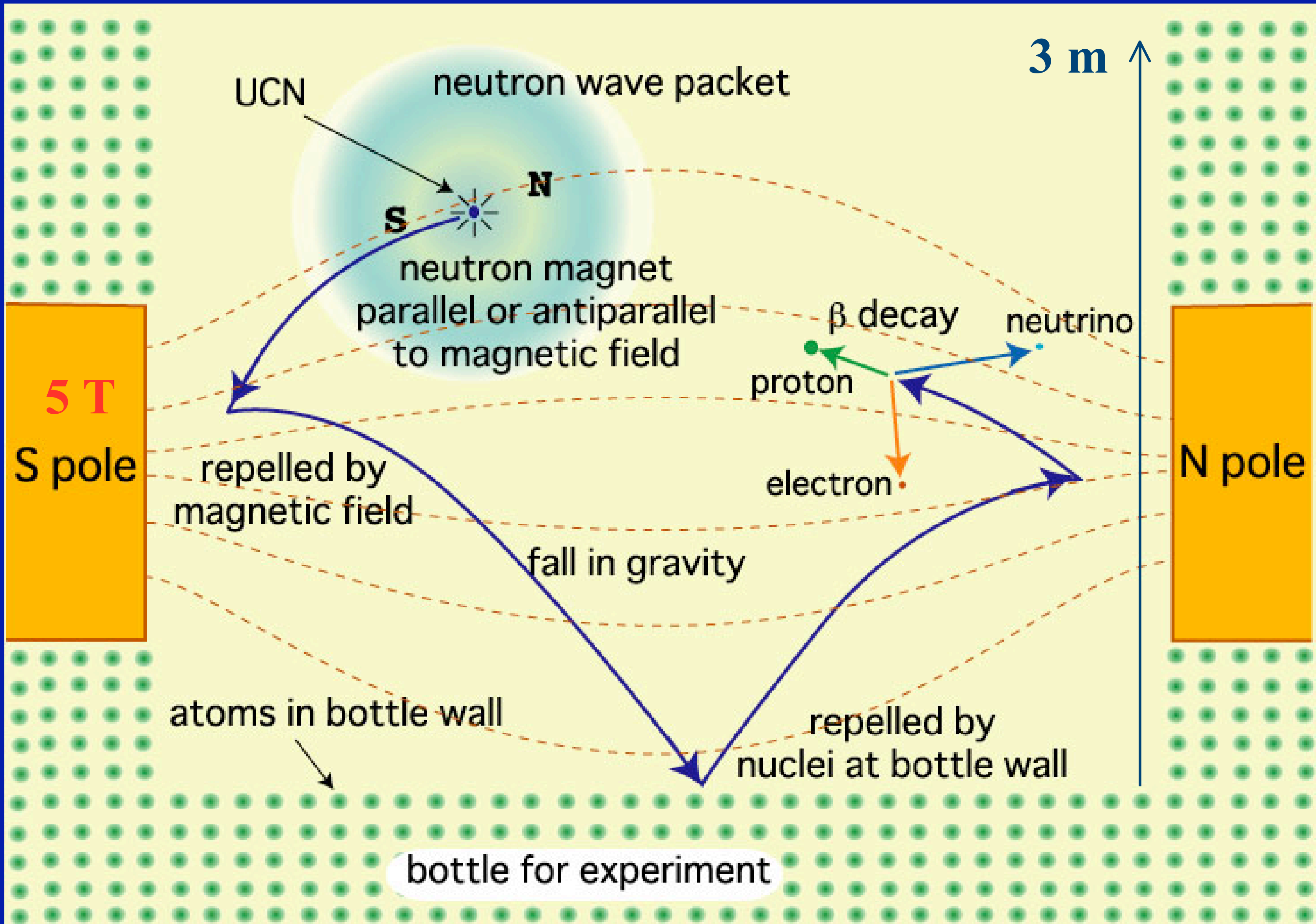
$\square \sim e^{\,ik.x} + f\, e^{\,ikr} / r$ $\square$ $1 - a/r = (a - r)/r$

$f = -1/4\square\ 2m/\hbar^2 \int d^3x\, e^{\,i(k - k').r}\, V$ $\square$ $V = 2\square\hbar^2/m\ a\, \square(r)$

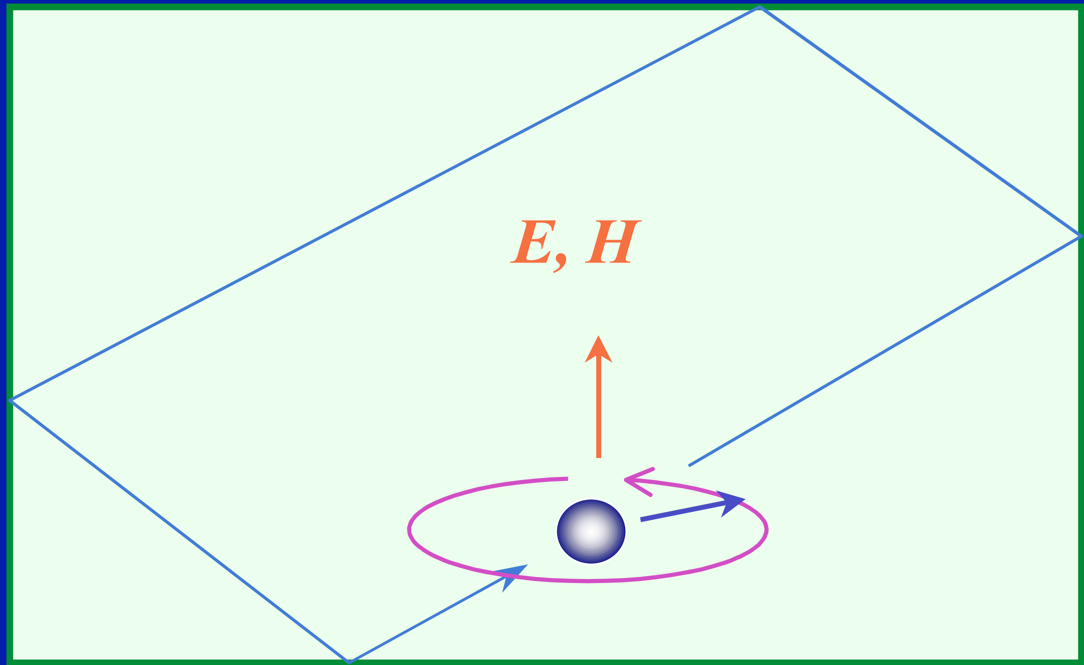
Neutron scattering length *a*



UCN: $E < 2$□$h^2/m\ Na$: 335 neV, $T < 3$ mK, $v < 7.5$ m/s



EDM measurement



$U(t, t_o) = \exp\{\, i\, (d_n E + \mu H)(t - t_o) / \hbar \}$

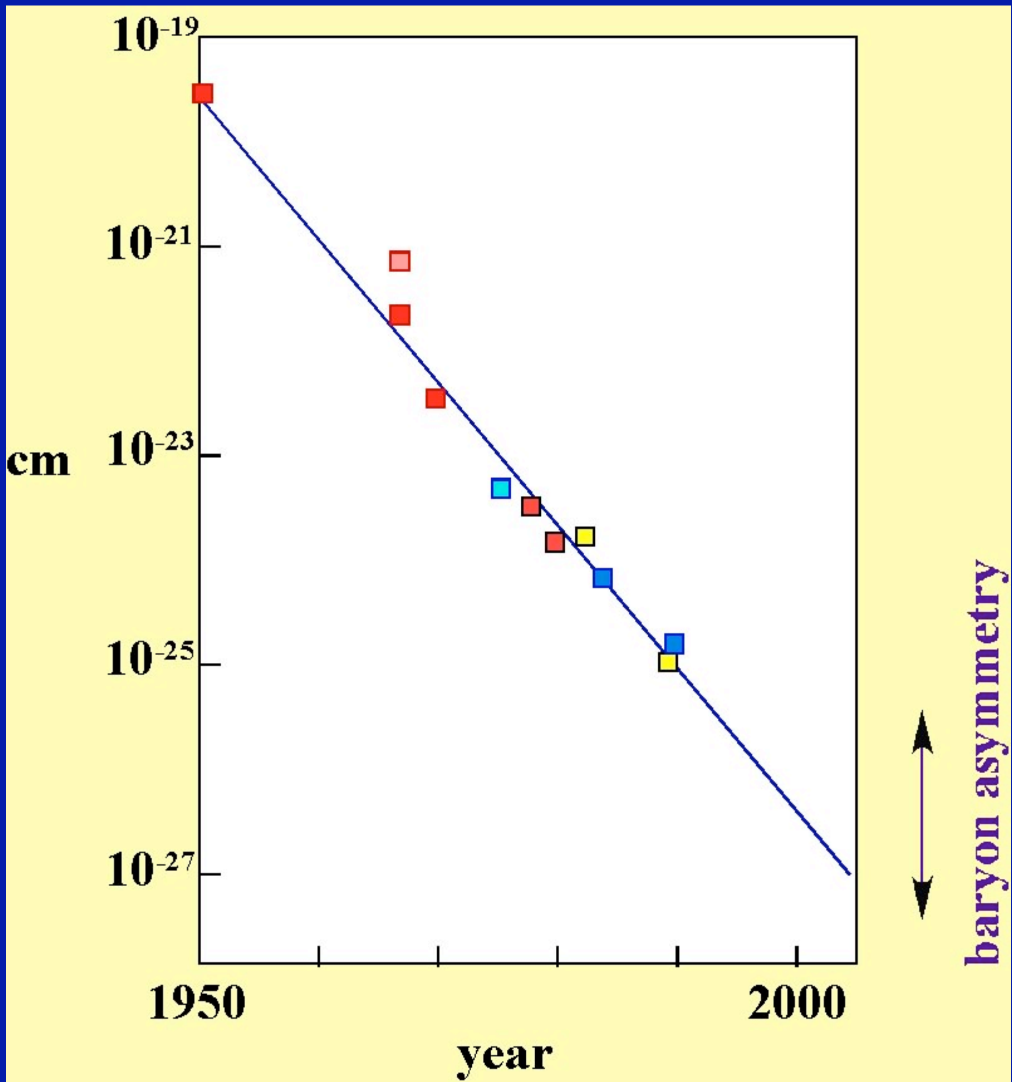
dynamical phase

neutron polarimetry

cancellation of

$E \times v$ effect

History of EDM



n EDM

10^{-31} cm standard model

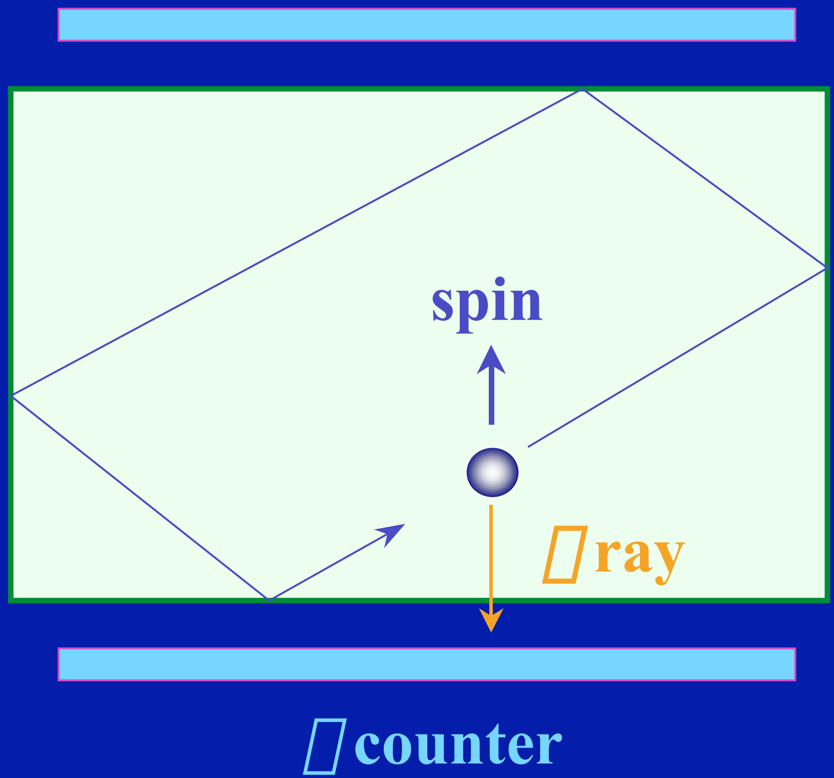
Baryon asymmetry

$n_B/100n_\gamma$

10^{-25} standard model

10^{-10}~10^{-11} obs.

β decay experiments **in a magnetic bottle**



neutron life time

β asymmetry with $\delta A/A \sim 10^{-3}$

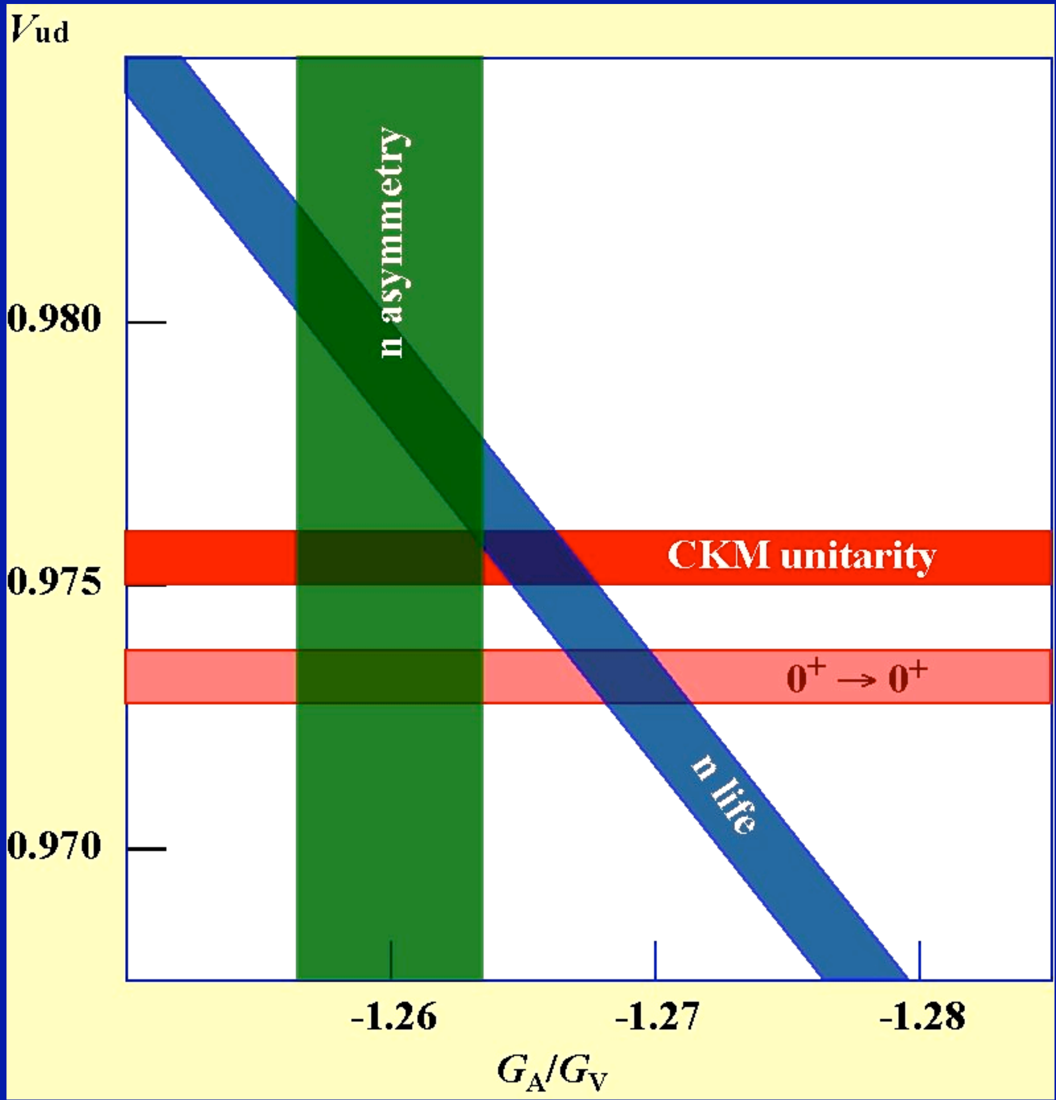
weak coupling constants

G_A and $G_V = G_F V_{ud}$

V_{ud}: test of CKM unitarity

$$(u, c, t)_L \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

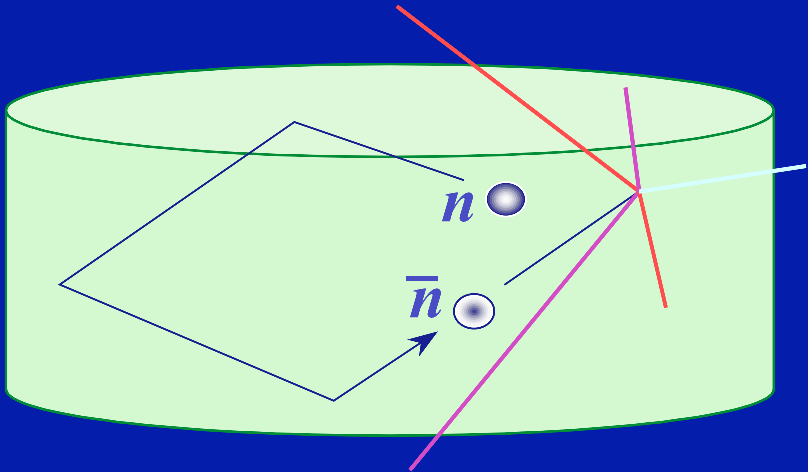
CKM unitarity



n-n̄ oscillation

$$\begin{pmatrix} E_1 & \Box \\ \Box & E_2 \end{pmatrix} \qquad \begin{matrix} 1: n \\ 2: \bar{n} \end{matrix}$$

1 to 2: $(\Box/\hbar)^2/[(\Box/\hbar)^2 + \Box_{21}{}^2/4]\ \sin^2\{[(\Box/\hbar)^2 + \Box_{21}{}^2/4]^{1/2}\, t\}$



5 pions event, 1.8 GeV

$\Box_{nn} = \hbar/\Box$

$\Box_{nn} > 8.6\ \Box\ 10^7$ s, n beam(1994)

$\Box_{nn} > 1.2\ \Box\ 10^8$ s, intranuclear

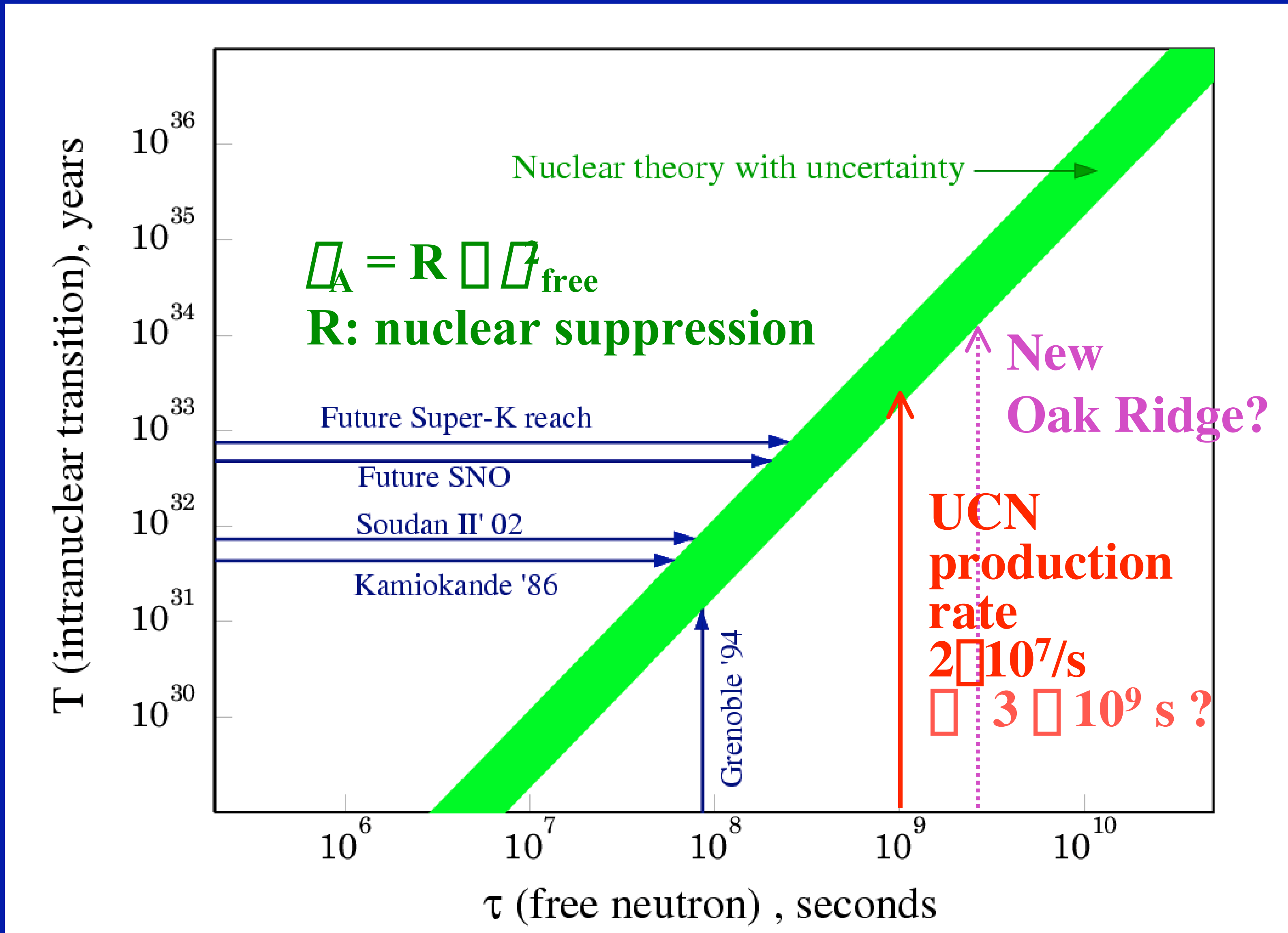
by PDG

□

10^9 s by bottled UCN

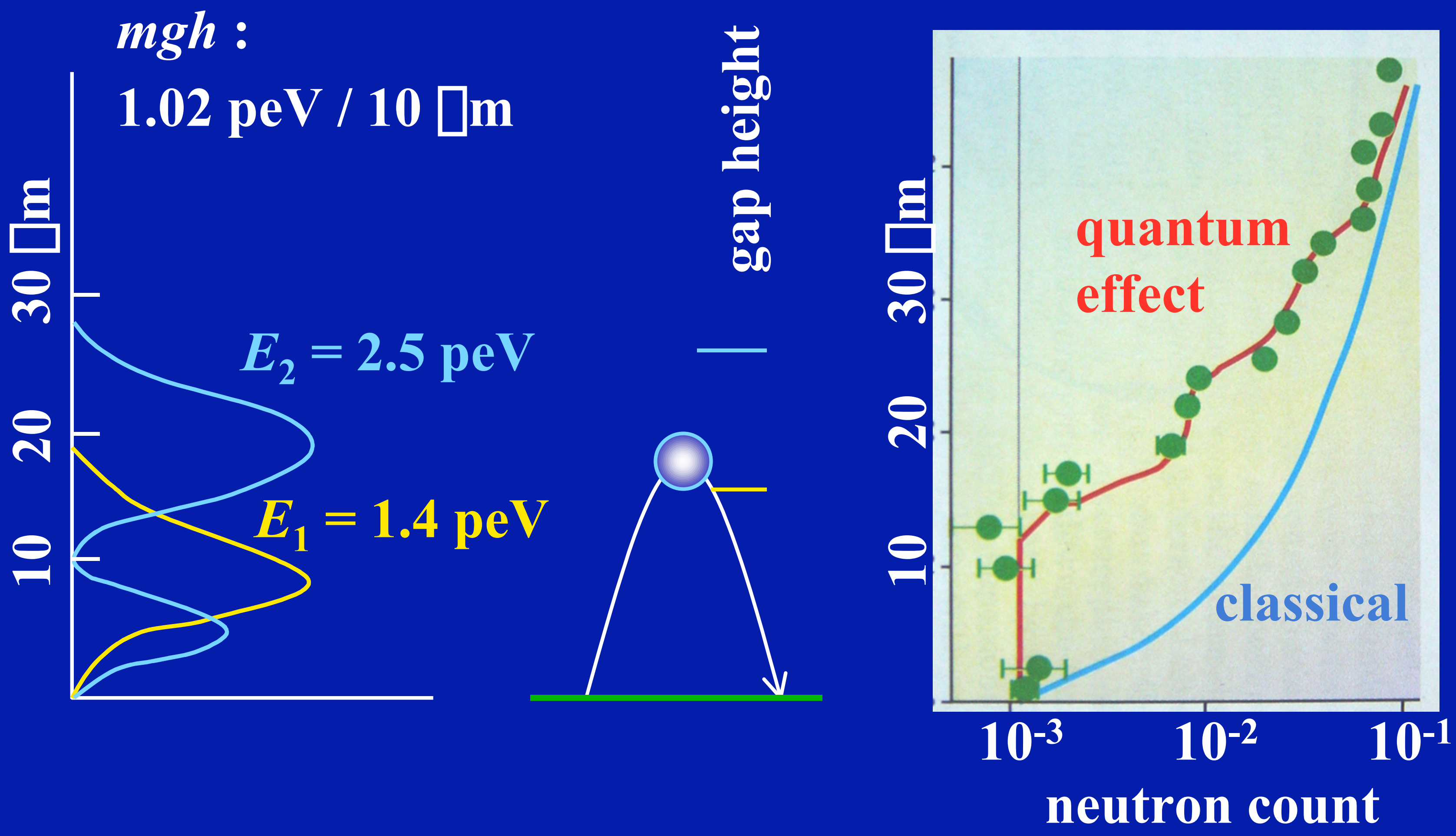
$10^{9\sim10}$ s by Mohapatra (2001)

n-n̄ oscillation time (Y. Kamyshkov)



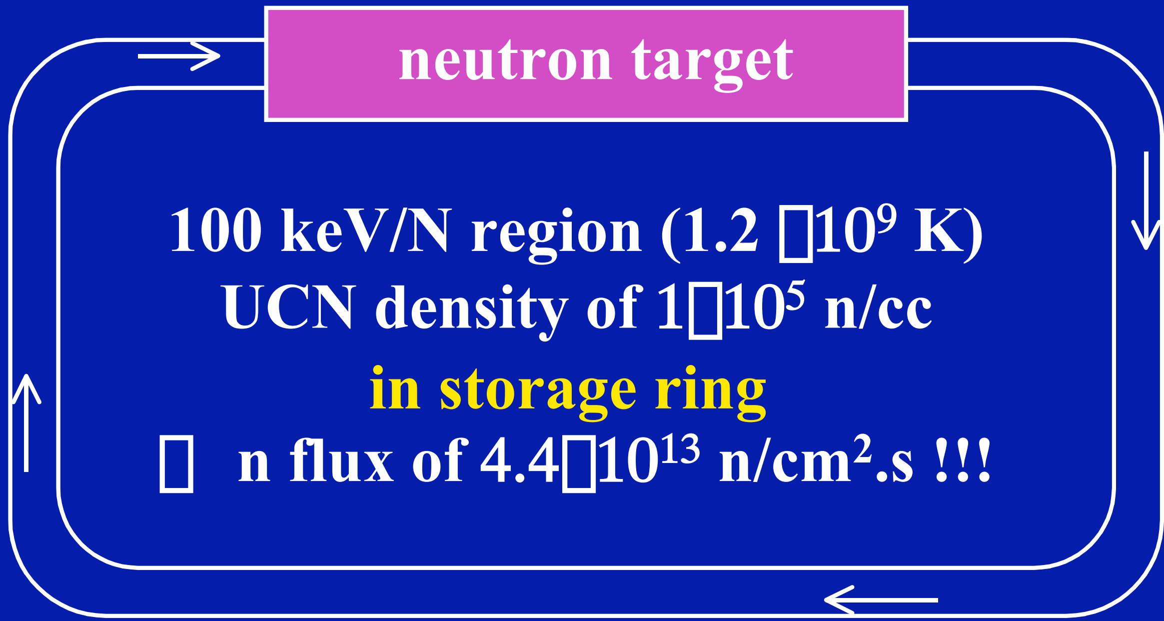
quantization under gravity

Nesvizhevsky et al.(2002)



Neutron target

for radioactive nuclear beam

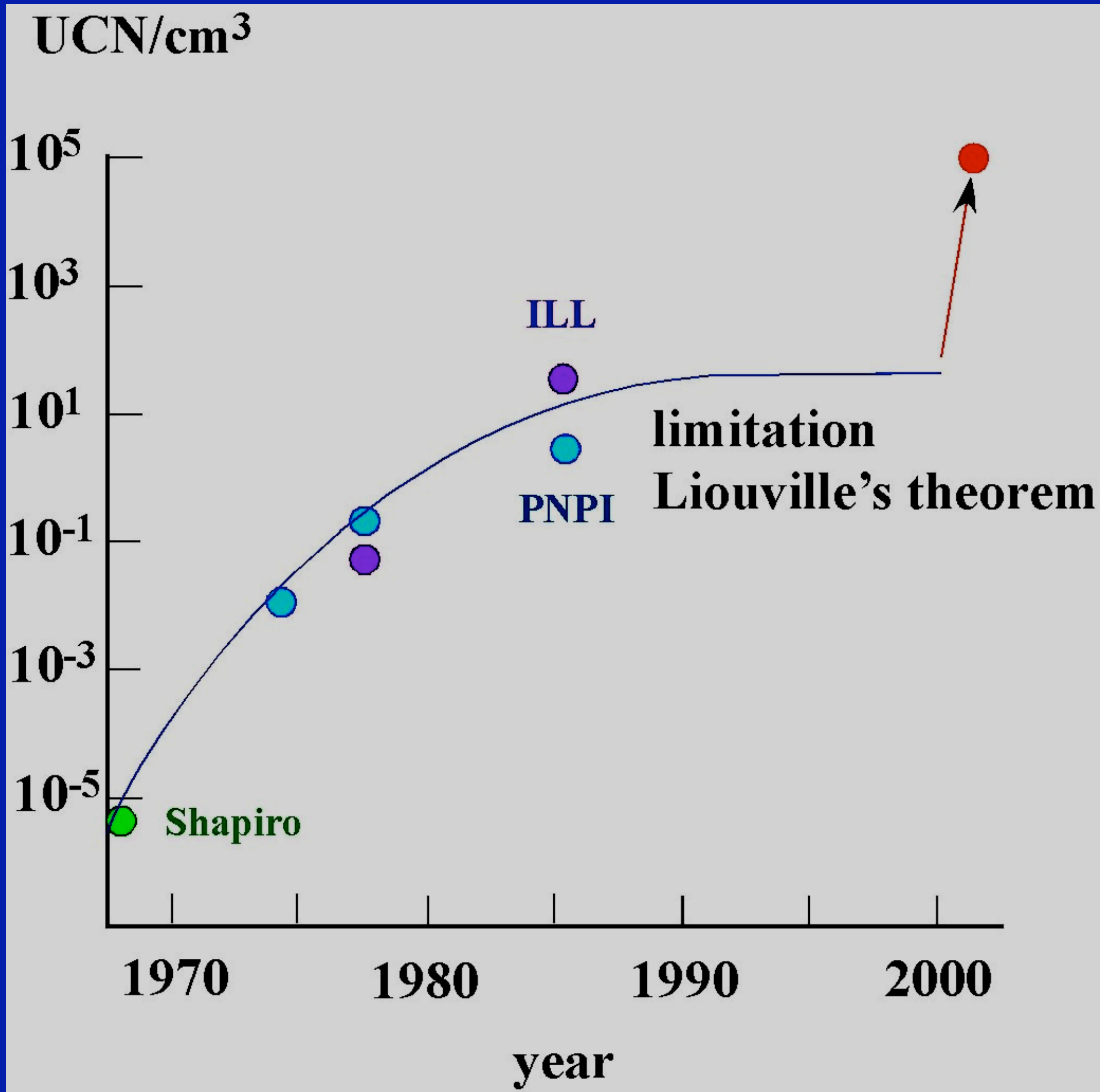


time averaged n flux of 1 MW JSNS 4×10^5 n/cm^2.s

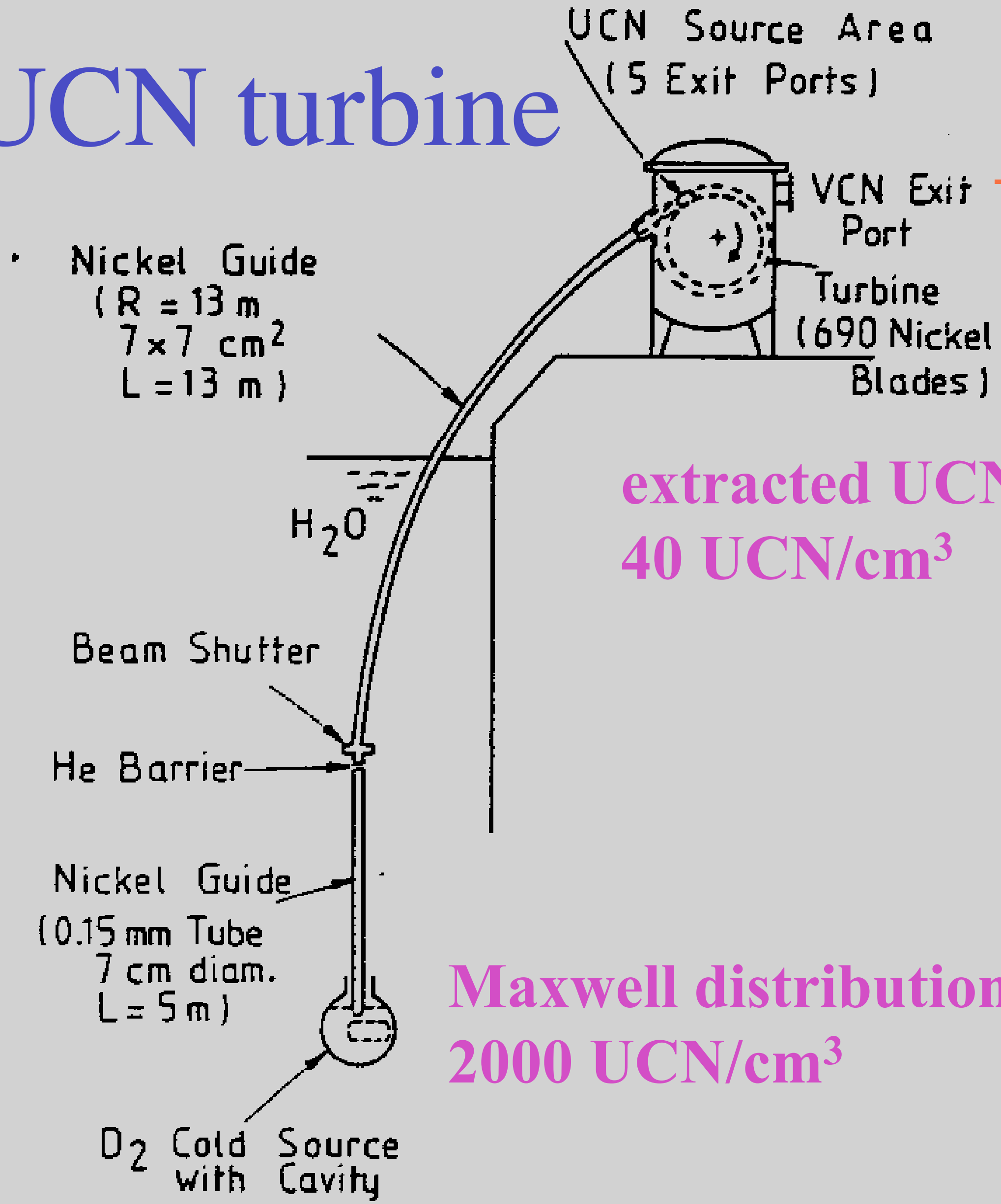
$\Delta E/E = 0.1$

surface physics

History of UCN production



UCN turbine



1~10
UCN/cm^3
at experiment

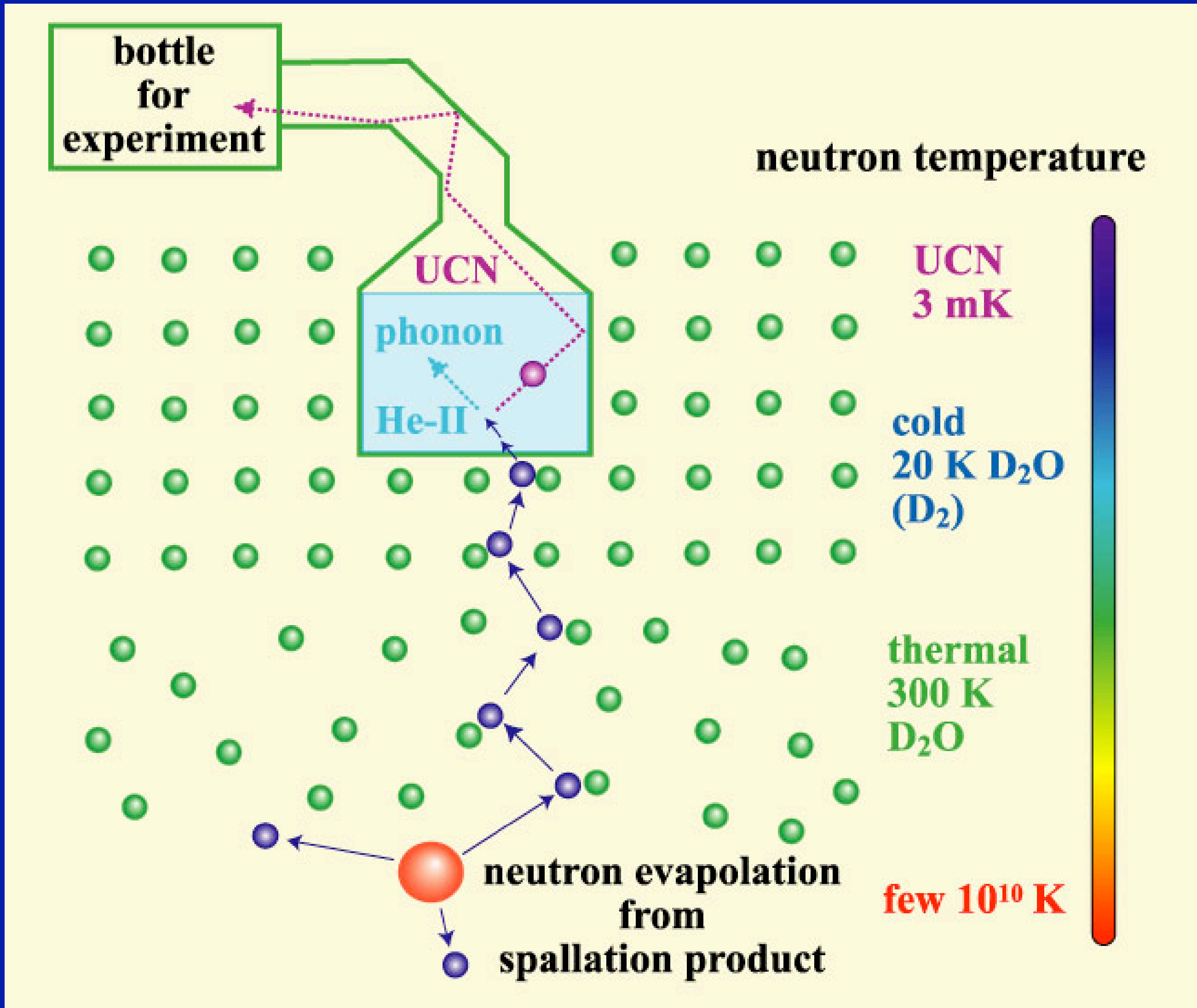
extracted UCN
40 UCN/cm^3

Maxwell distribution
2000 UCN/cm^3

Superthermal UCN production

1977 (He-II)	proposal for reactor	(Golub, Pendlebury)
1981	proposal for spallation source	
1983 (solid D_2)	proposal for thin film source	
1983 (He-II)	experiment	(ILL)
1987 (He-II)	proposal for spallation source	(Yoshiki)
1990 (He-II)	experiment	(KEK at JAERI)
1996 (He-II)	proposal on dedicated UCN	(present)
1998 (solid D_2)	proposal on dedicated UCN	(Los Alamos)
1998 (solid D_2)	proposal on dedicated UCN	(PSI, PNPI)
1999 (solid D_2)	experiment on dedicated UCN	(Los Alamos)
2000 (He-II)	experiment	(NIST)
2000 (solid D_2)	proposal	(Munich)
2001 (He-II)	experiment	(ILL)
2001 (He-II)	experiment on dedicated UCN	(present)
2002 (solid D2)	proposal	(North Carolina, Indiana)

A new UCN production



Lethargy: □

$= -\mathrm{ave}(\ln(E_f/E_i))$

$= 2/(M/m + 2/3)$

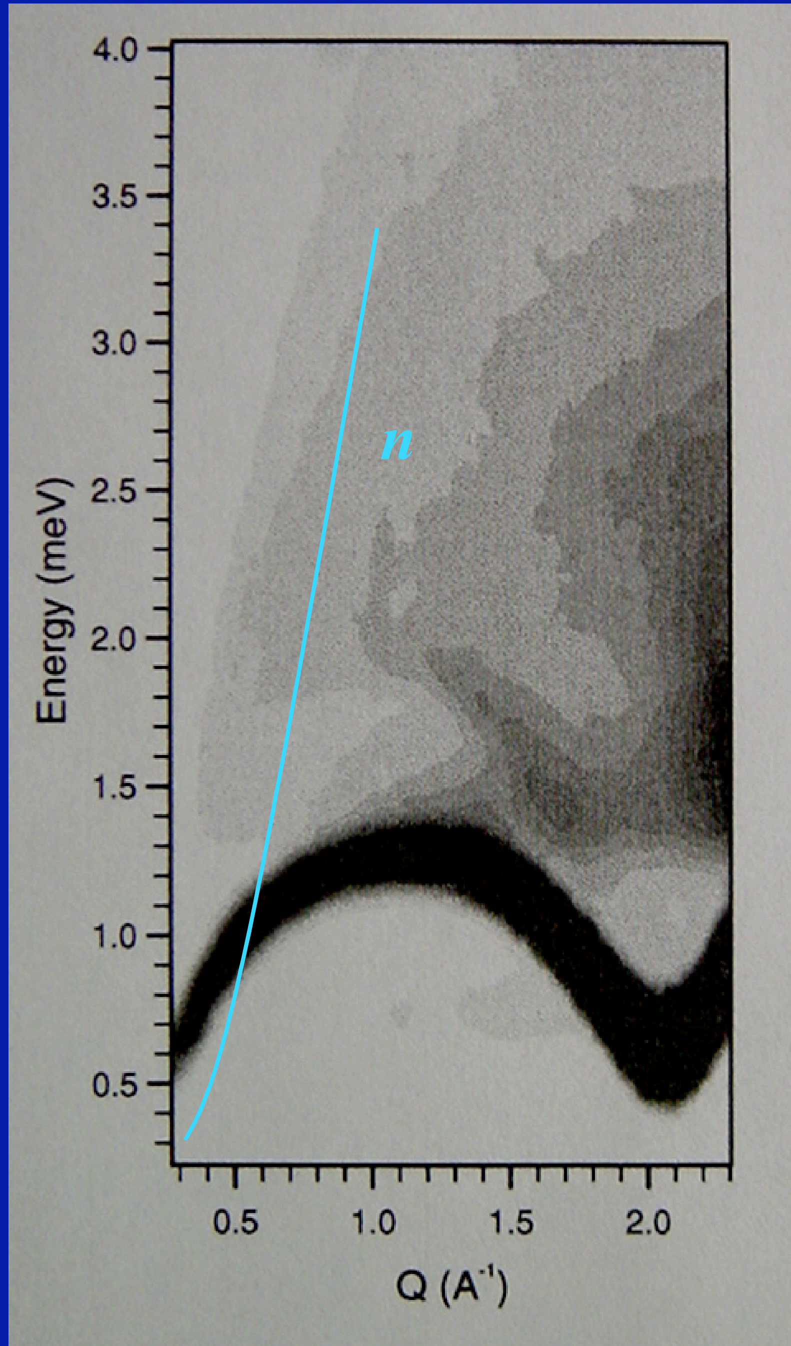
UCN production cross section

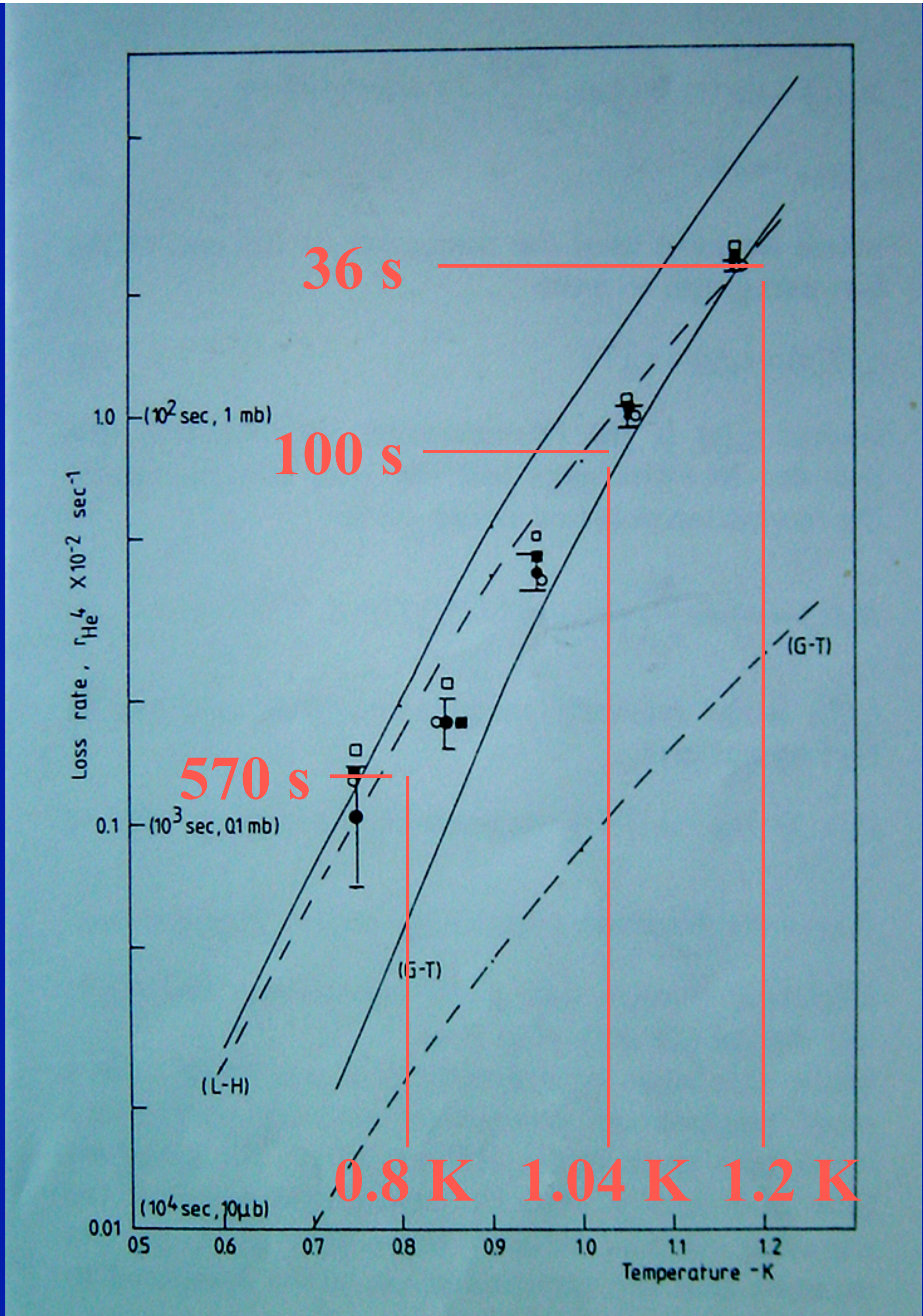
$d^2\square/dQd\square$
$= k_f/k_i\ a^2\ S(Q,\square)$
$= Z(Q)\square(\square - \square(Q))$
$+ S_{II}(Q,\square)$

1971 Cowley and Woods
1994 Andersen et al.
1999 Gibbs et al.

$Z(Q)$ = 0.1 at 1 meV

$\square_{ucn} = \int_0^{E_c} \square\, N_{He}\, \square_n\, \square dE$



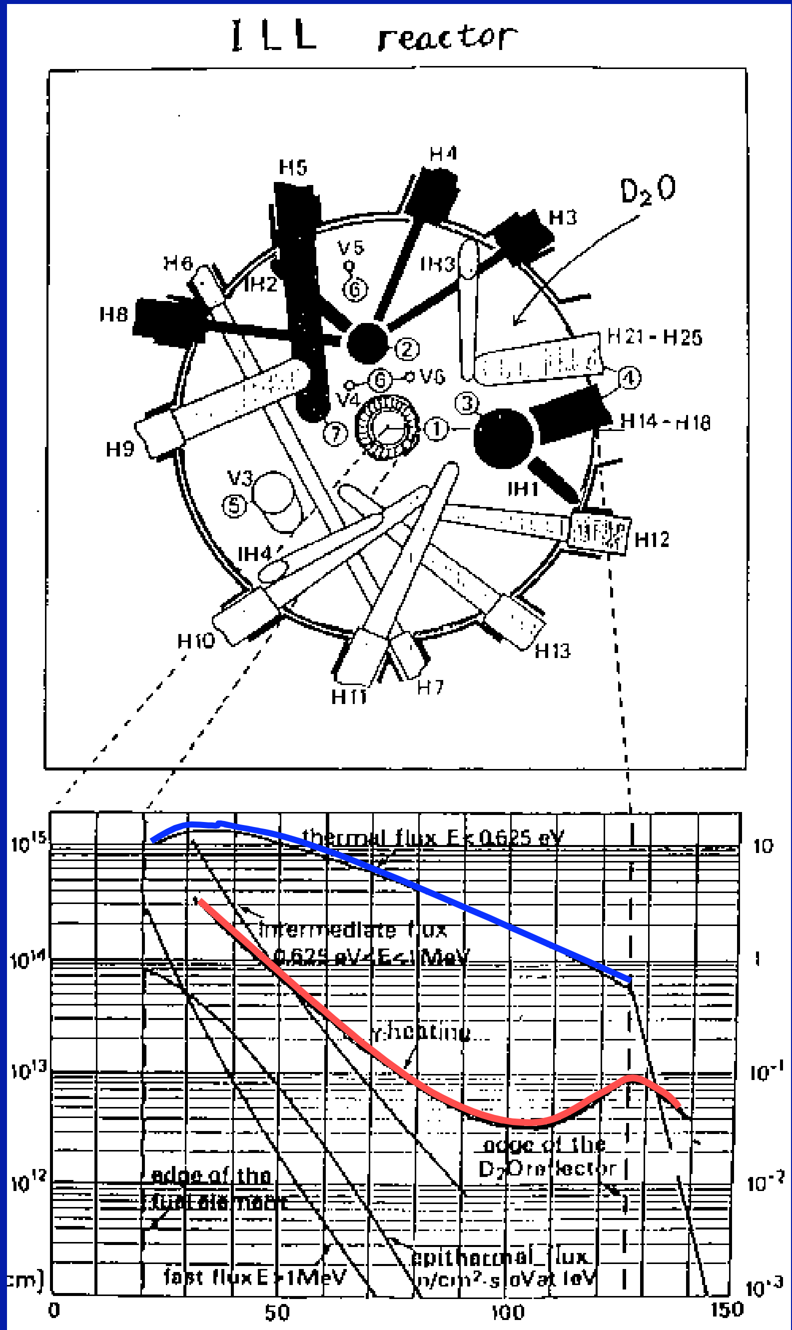


UCN storage time

phonon up-scattering rate in He-II
1/ µ T^7

Golub et al. (1983)

ILL 60MW reactor



n flux
n/cm^2.s

10^{15}

10^{14}

10^{13}

10^{12}

γheating
W/g

10

1

10^{-1}

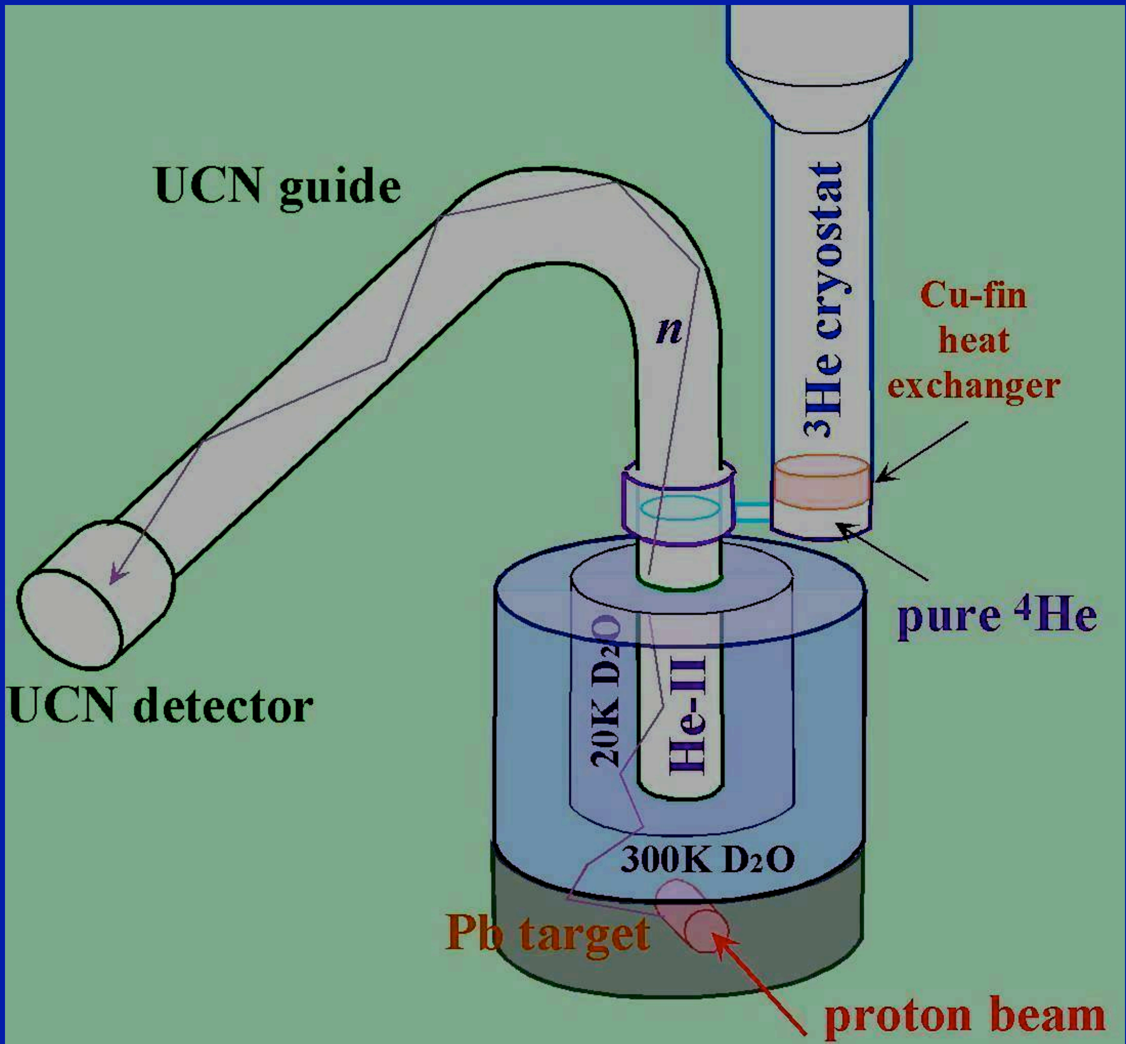
10^{-2}

□heating

spallation neutron source
(7 *n/p* at E_p = 500 MeV)

small □/n ratio
free geometry for target moderator configuration
easy to place □shield

He-II Spallation UCN source



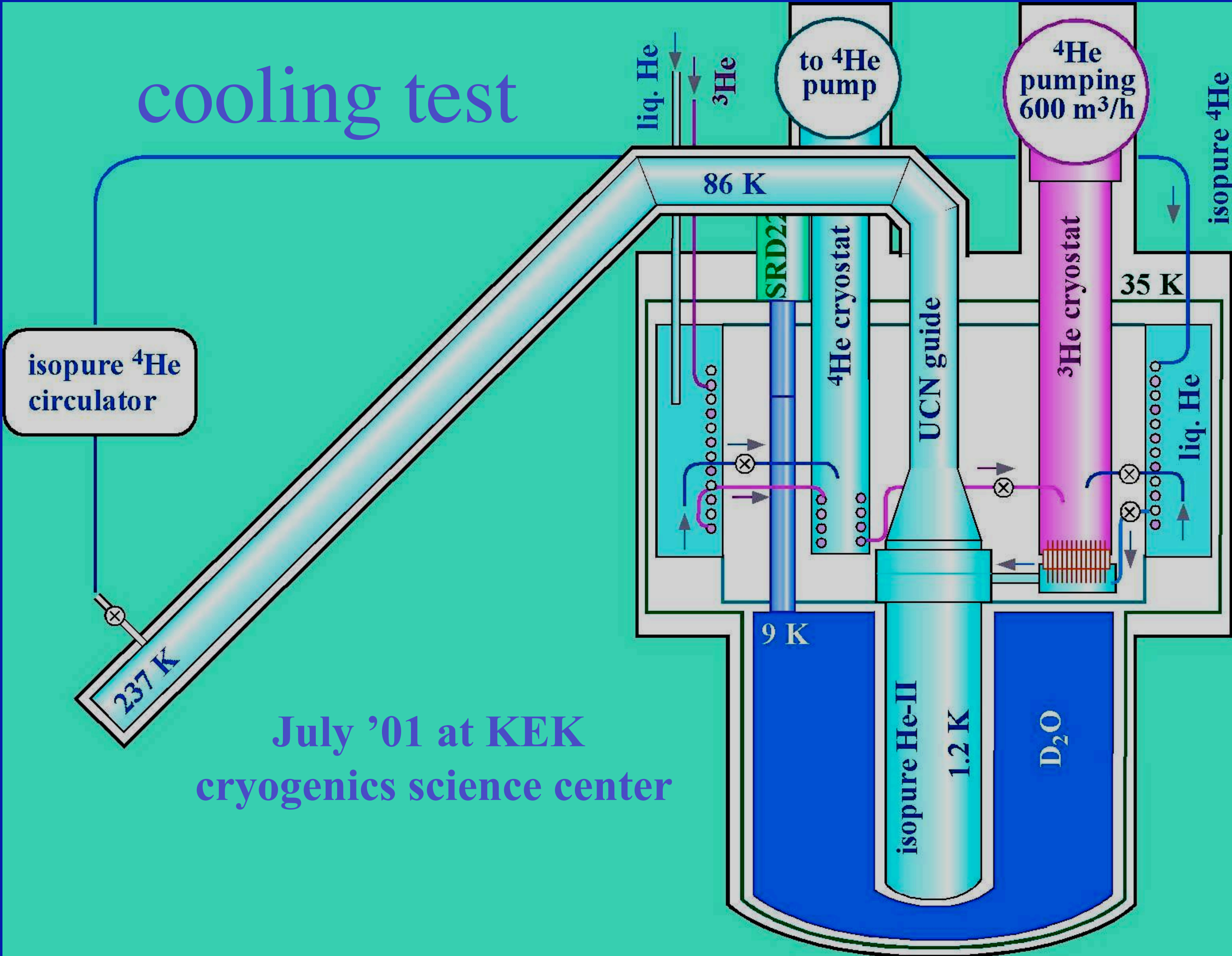
1996 proposed at KEK

1998 Monte Carlo
- **12 kW proton**
- **1000 UCN/cm^3 s**
- **3 W heating**
- **2000m^3/h pump at 0.8K**

1999 no cryogenic wall
- **between He-II bottle**
- **and exp. bottle**
- **100 s storage time**
- **10^4~10^5 UCN/cm^3**

2000 funded

cooling test



July '01 at KEK
cryogenics science center

UCN cryostat at fabrication

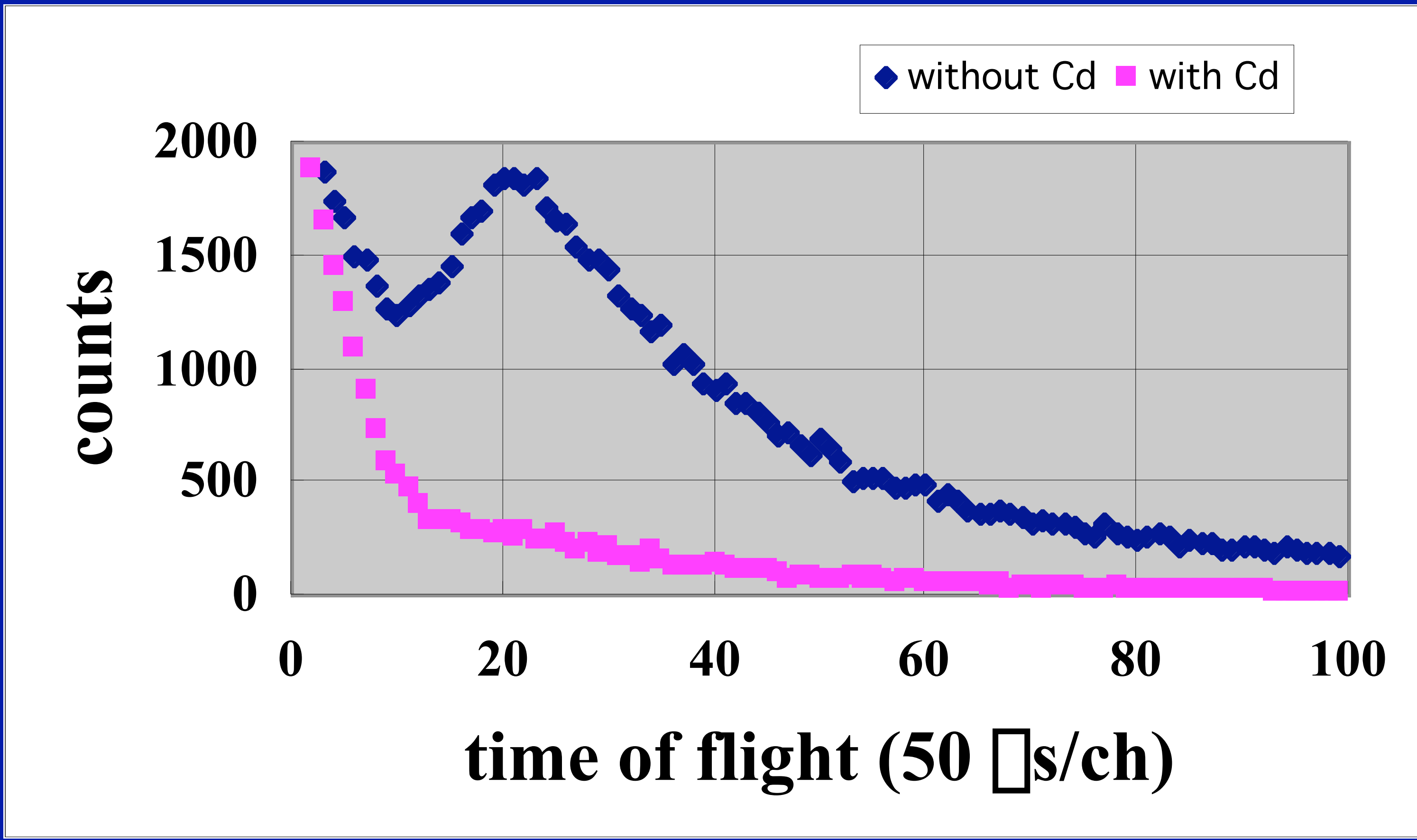
D_2O bottle at 300 K

Neutron production test

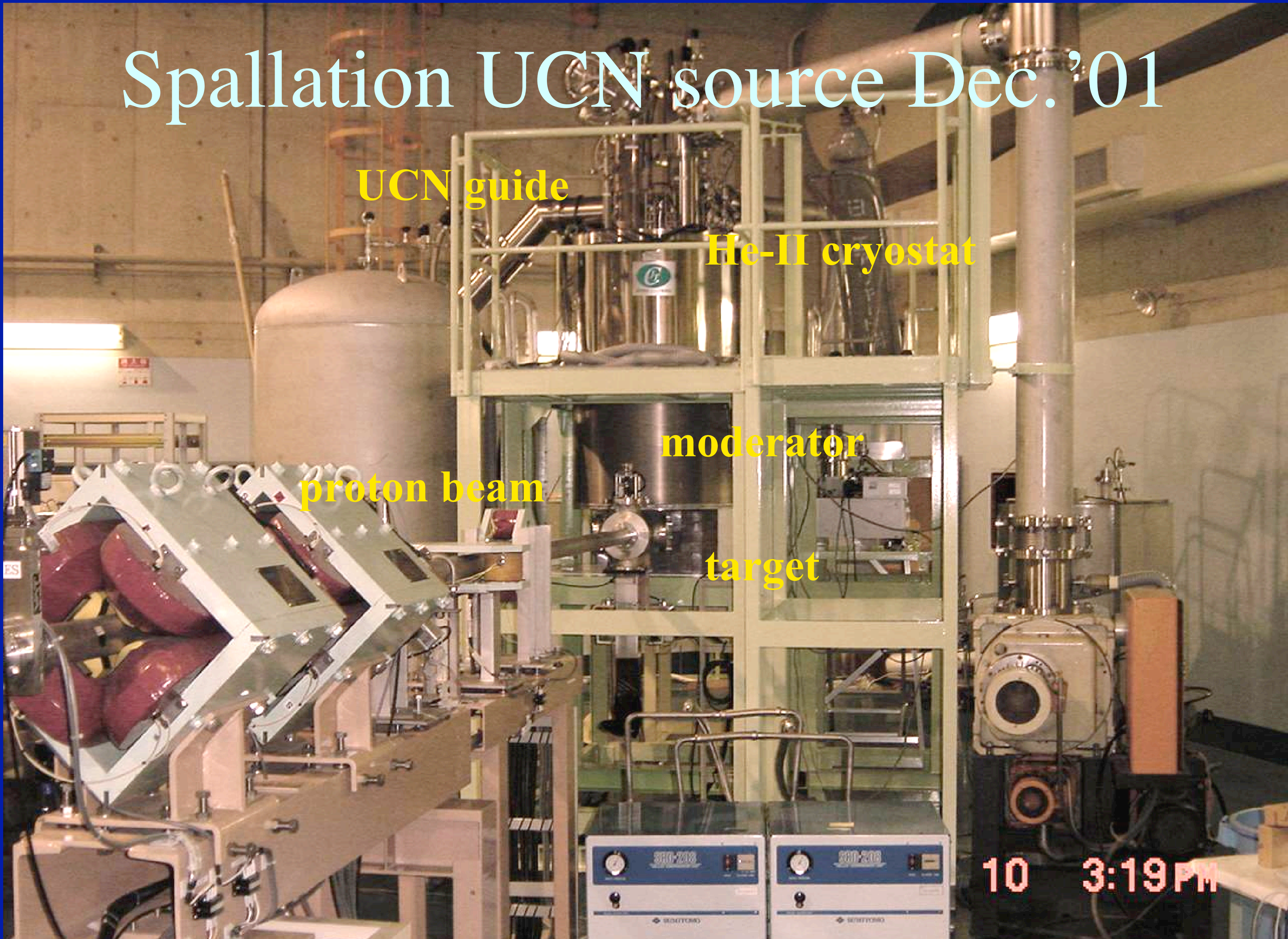
Oct. '01
at Osaka

UCN counter
^{3}He counter

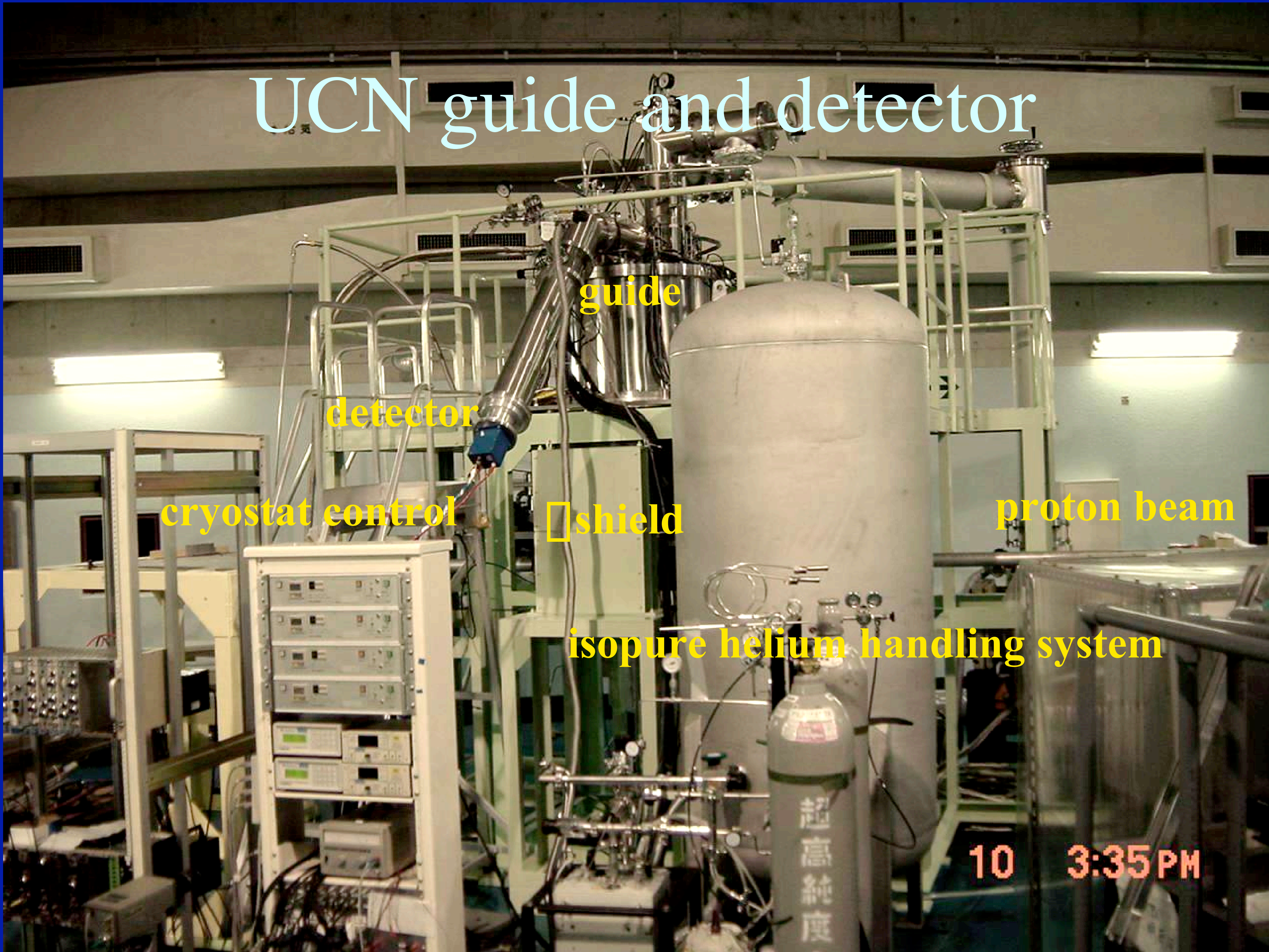
TOF spectrum by ^{3}He counter



Spallation UCN source Dec.'01



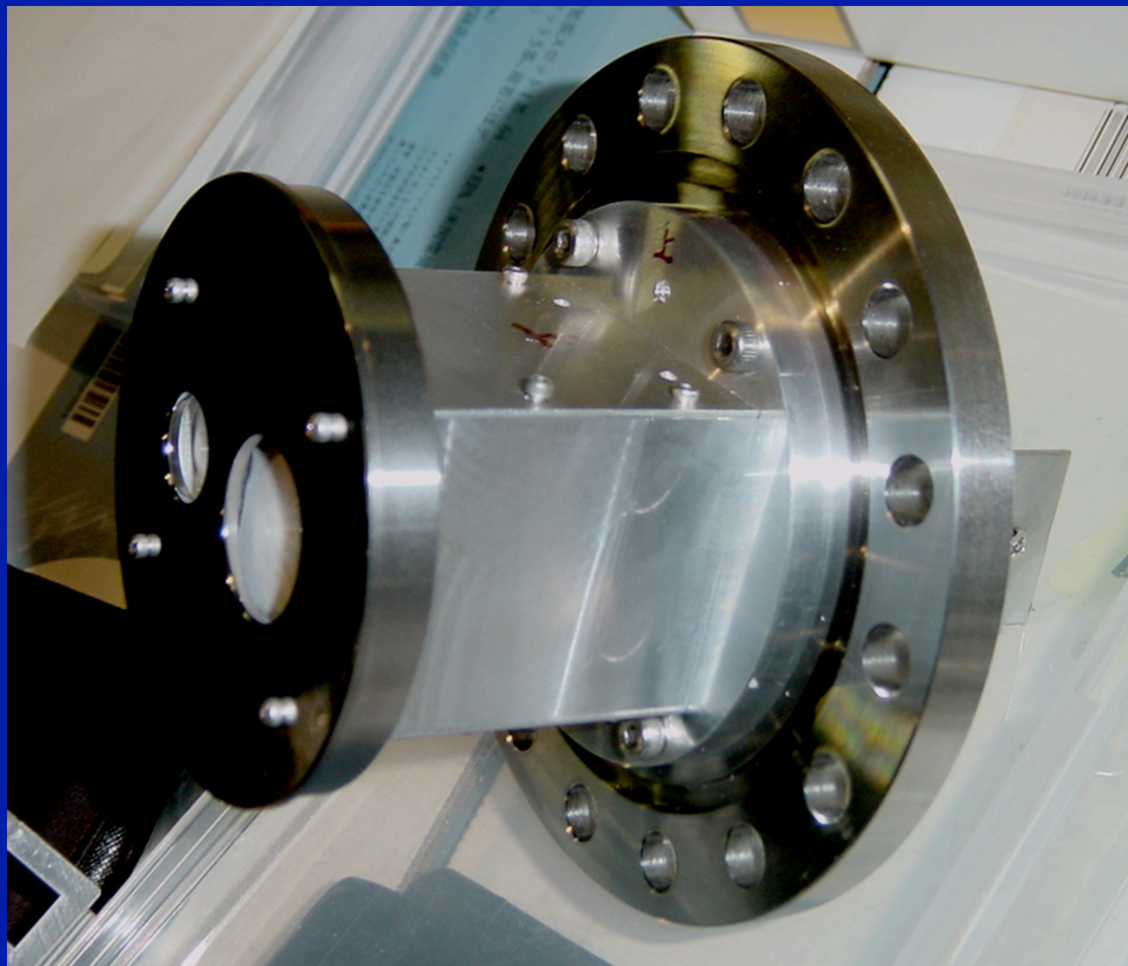
UCN guide and detector



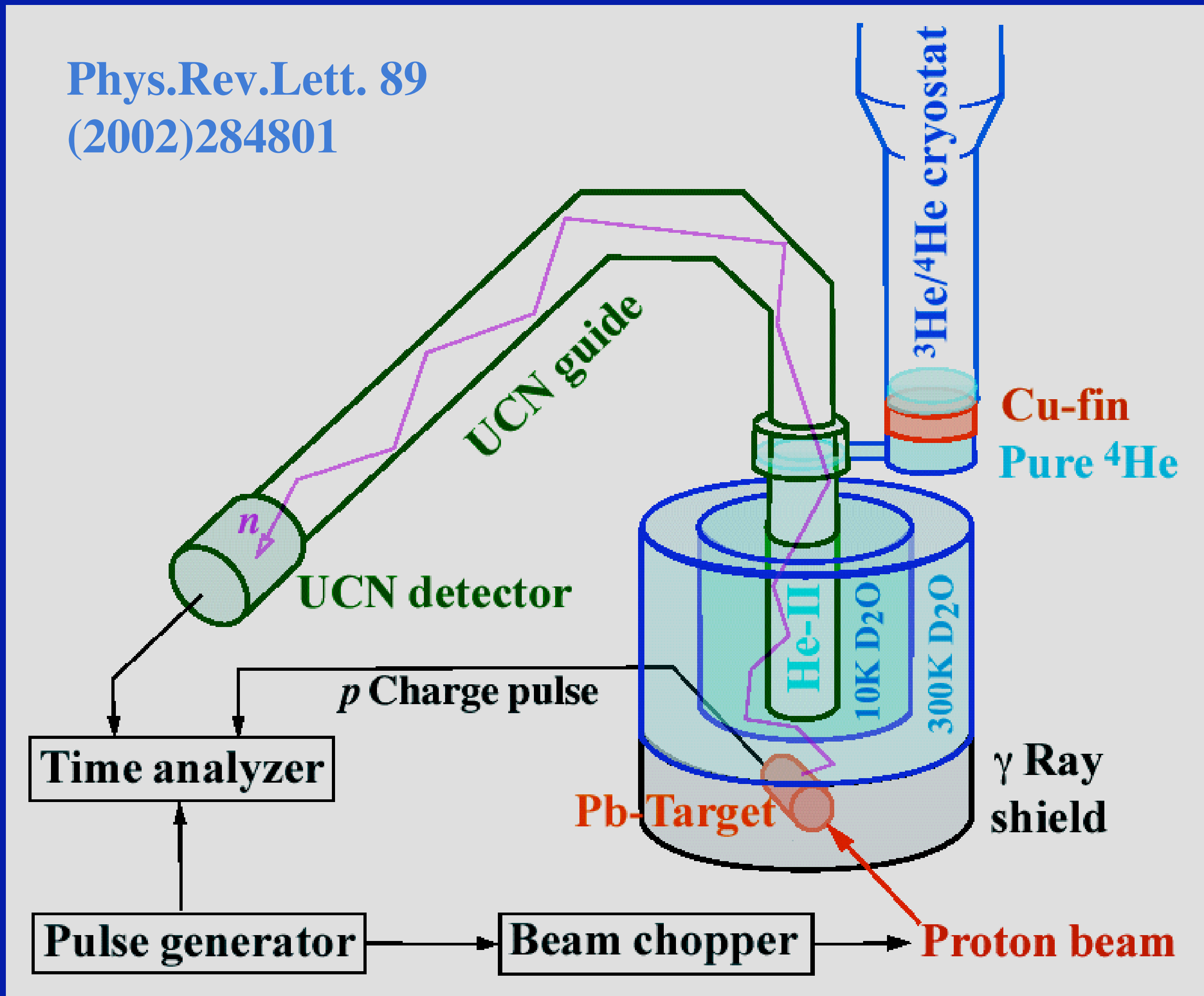
UCN detector

^{6}LiOH-coated Si-PIN

(depletion layer: 200 μm, ^{6}LiOH: 0.5 mg/cm^{2})

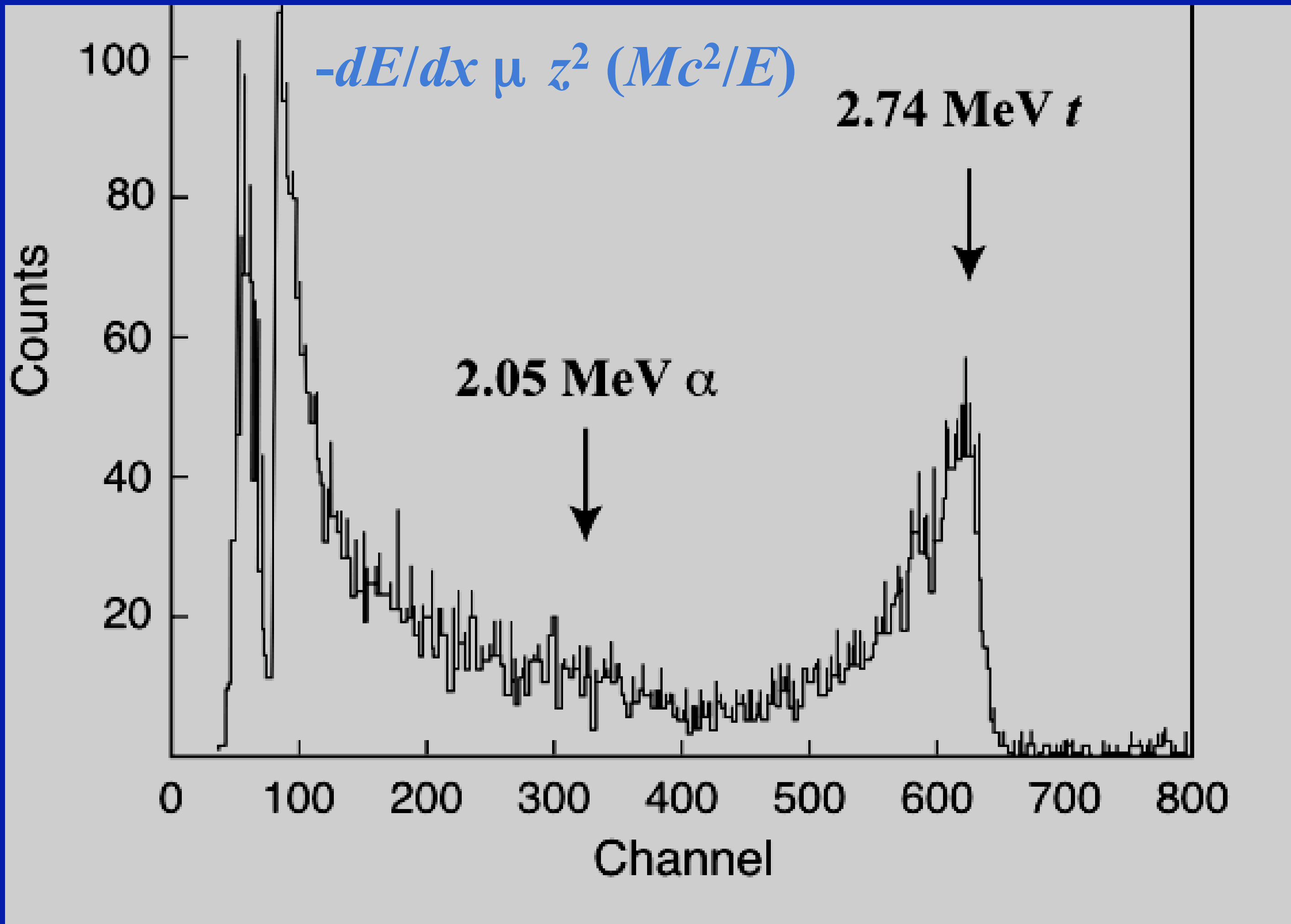


UCN production experiment



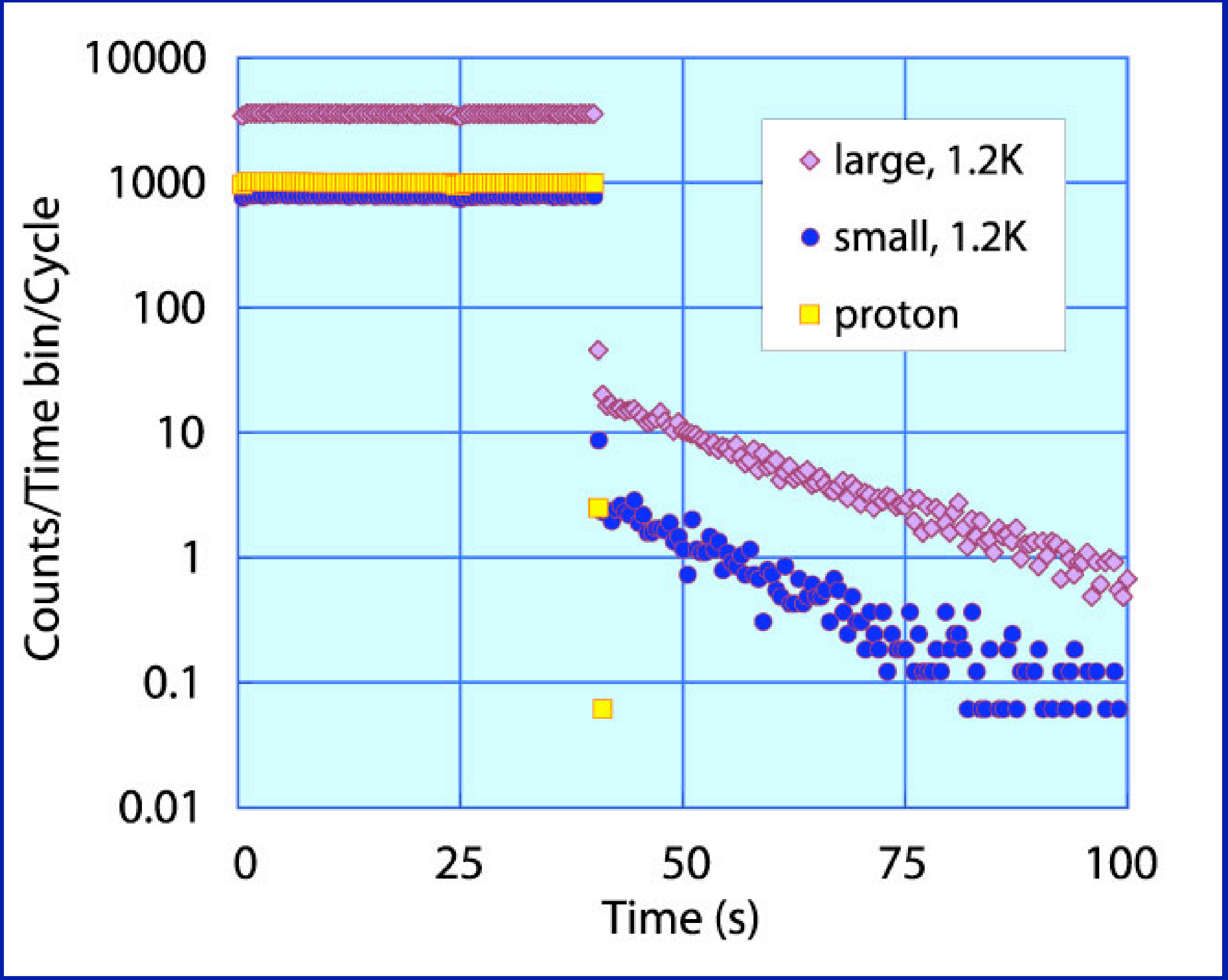
^{6}Li(n, α)t neutron signals

Phys.Rev.Lett. 89(2002)284801



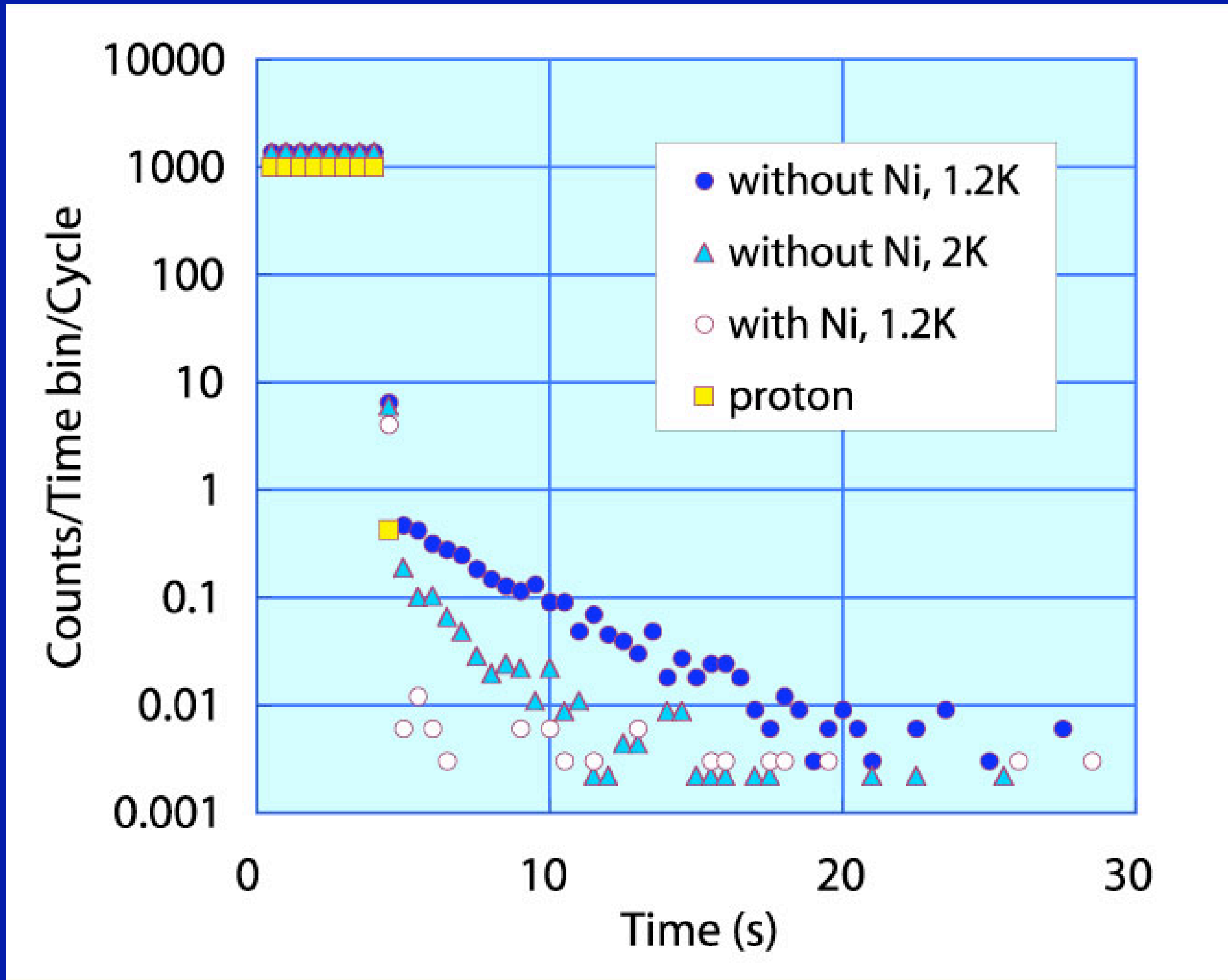
Neutron time spectrum

Phys.Rev.Lett. 89(2002)284801



Temperature and Fermi potential

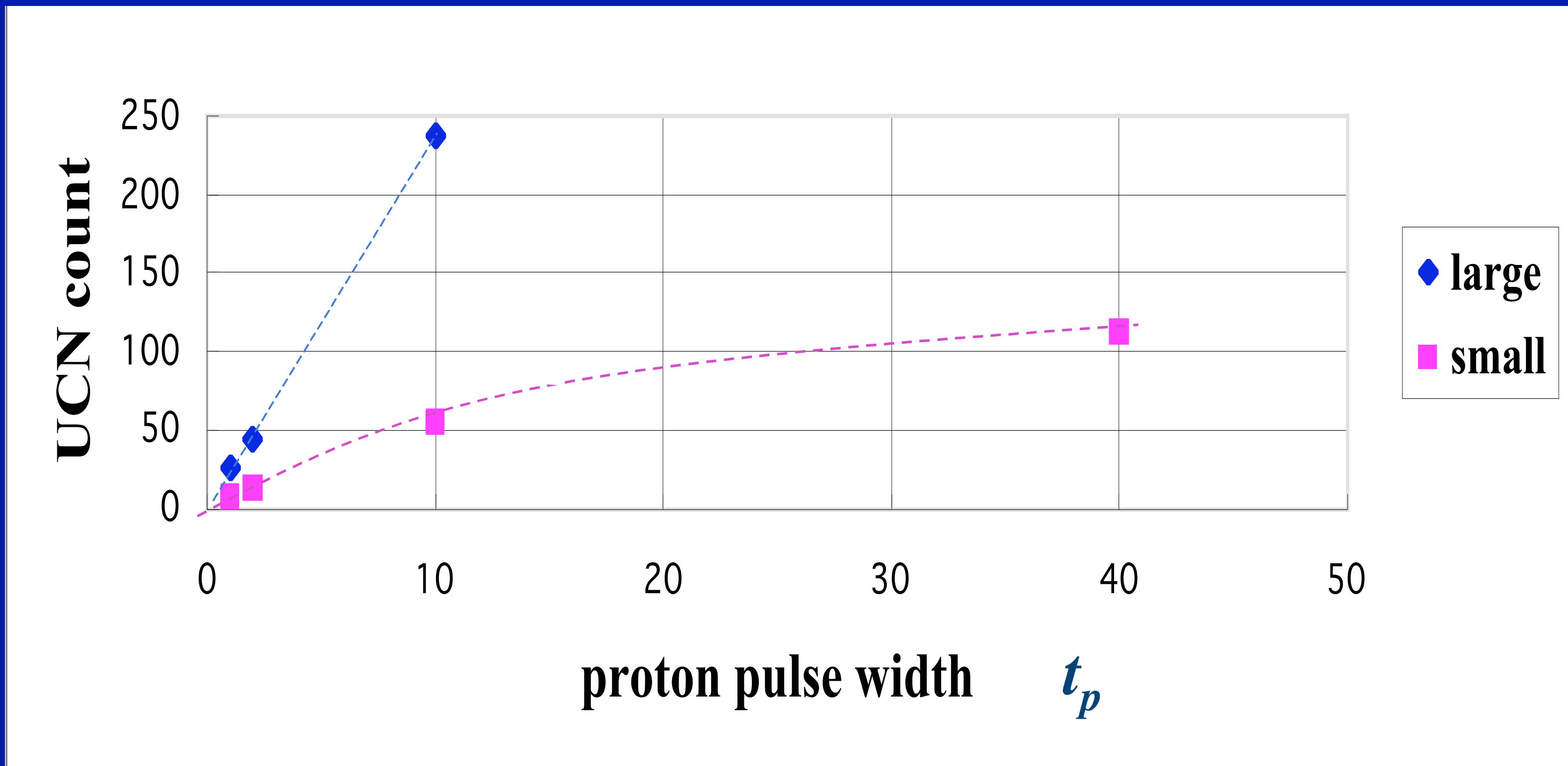
Phys.Rev.Lett. 89(2002)284801



Proton pulse width

$$\Box_{ucn} = \int_0^{E_c} \Box_{coh}(E/E_{in})^{1/2}\Box\, S(k_{in})\, N_{He}\Box_{n}\, \Box[1 - \exp(-t_p/\Box)]\, dE$$

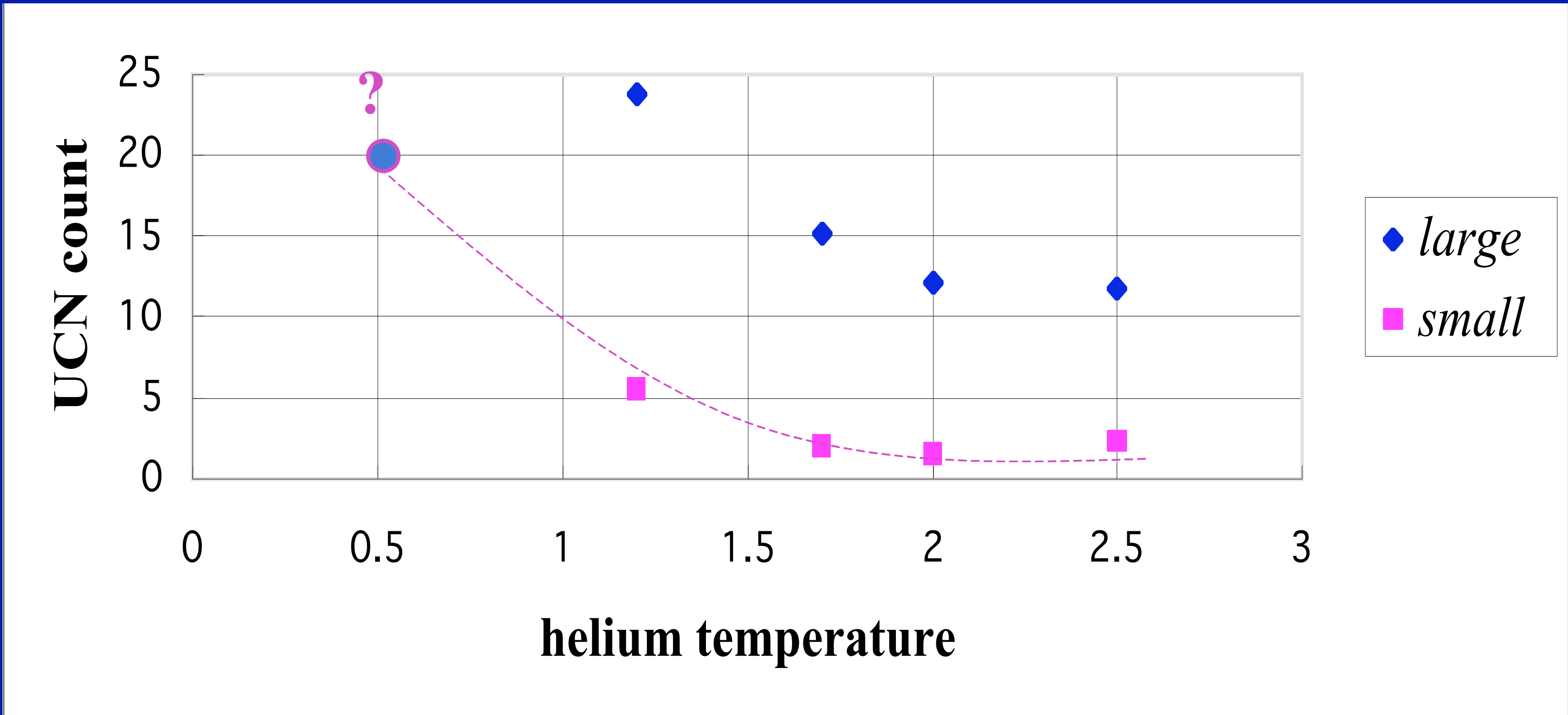
E_c : critical energy of UCN



Diffusion from source to detector

$J(z) = (nvA/4) \,/\, [\cosh(z/L) + \sinh(z/L)]$
$L^2 = D$ □

1 s proton pulse width



UCN density

Present: 1.4 UCN/cm^3 for E_c < 100 neV at 156W, τ= 14 s (1.2K)
[few UCN/cm^3 in ILL(60 MW) experimental bottle
400 expected at Los Alamos, 2000 expected at PSI]

density scaling to full operation	**2×10^5 UCN/cm^3**
total volume of 20 *l*	
increase in cold neutron flux Φ_n, production rate	
***p* beam power of 30 kW**	**× 30000/156**
neutron reflector	**× 2**
D_2 cold moderator	**× 8 (expected)**
increase in storage time τ to 100 s	**× 100/14**
diffusion effect	**× 2.5 (expected)**
increase in critical energy E_c	**× 2.5**
(He-II bottle of beryllium)	

Superthermal source material

	solid D_2 Los Alamos, PSI , Indiana (Munich, North Carolina)	He-II ours
production rate	large	not so large
storage time	very short	very long
heat conduction	limited	much better than any other material
extraction loss	large	negligible
(mean free path □	1 ~ 8 cm	>> 1 m)
(Fermi potential	high	negligible)

summary

The present UCN source is the first He-II source,

has no limitation from Liouville's theorem and
extraction losses

good for **high intensity UCN production**
(high power operation)
storage experiment
(no UCN absorption)

will make a break through in UCN physics