A new UCN source at TRIUMF for EDM, $\beta$ decay, gravity etc.

For these experiments, Phase space density is crucial.

Momentum space is limited by Fermi potential $(E_c = 100\sim200 \text{ neV})$ and magnetic potential $(60 \text{ neV/T})$, real space by bottle size

$$V_F = \frac{(2\pi\hbar^2/m)aN}{1}$$
Present UCN source at ILL

- 50 UCN/cm$^3$ in source $E_c = 335$ neV
- 2 to 3 UCN/cm$^3$ in an experimental bottle of $E_c = 100$ neV
- 0.7 UCN/cm$^3$ in EDM cell

UCN density is limited by Liouville’s theorem for the deceleration by gravity and Doppler effect.
New UCN sources
LANL, PSI, NCSU, Munich, ILL, SNS and Ours

use neutron cooling by phonon
no limitation of Liouville’s theorem, we can use phonon phase space

Production rate, $P_{UCN}$

$$P_{UCN} = \int \int \sigma_{coh}(E_{in} \rightarrow E_{UCN}) \ \Phi_n(E_{in}) \ N \ dE_{in} \ dE_{UCN}$$

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

$$\rho_{UCN} = P_{UCN} \times \tau_s \ (storage \ lifetime)$$
A new UCN production
Cold neutron flux $\Phi_n$

- **Ours 20kW:** $\Phi_n = 2 \times 10^{12} \text{n/cm}^2/\text{s}$
- **PSI 1.2MW:** $\Phi_n = 2.6 \times 10^{13} \text{n/cm}^2/\text{s}$
- **NCSU 1MW:** $\Phi_n = 1 \times 10^{12} \text{n/cm}^2/\text{s}$
- **SNS 1.5MW:** $\Phi_n \sim 10^8 \text{n/cm}^2/\text{s}$
- **ILL 60MW:** $\Phi_n = 10^{9-10} \text{n/cm}^2/\text{s}$

Capture flux: $\times 10^{-3}$

**UCN source**
UCN production rate $P_{\text{UCN}}$

In our He-II

$$P_{\text{UCN}} = (2-4) \times 10^{-9} \, \Phi_n/\text{cm}^3/\text{s},$$


= 0.37~0.73 \times 10^4 \, \text{UCN/cm}^3/\text{s}

20 kW

In Los Alamos SD2

$$P_{\text{UCN}} = 4.4 \times 10^4 \, \text{UCN/cm}^3/\text{s},$$


76 kW

In PSI SD2

$$P_{\text{UCN}} = 2.9 \times 10^5 \, \text{UCN/cm}^3/\text{s},$$


1.2 MW
Storage time $T_s$

He-II [Golub et al. (1983)]
phonon up-scattering, $1/T_{ph} \propto T^7$
$T_{ph} = 600 \text{ s at } T_{He-II} = 0.8 \text{ K}$

$\beta$ decay lifetime, $T_\beta = 886 \text{ s}$

wall loss, $T_{wall} = 300 \text{ s}$

$T_s = 150 \text{ s}$

$T_{ph} = 40 \text{ ms at } T_{SD2} = 8 \text{ K}$

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

$T_a = 150 \text{ ms}$

$T_s = 24 \text{ ms}$

diluted in vacuum
$T_s = 1.6 \text{ s, } 0.24 \rightarrow 9.6 \text{L Los Alamos}$

$T_s = 6 \text{ s, } 27 \text{L} \rightarrow 2 \text{ m}^3 \text{ PSI}$
Extraction from source

Vacuum

diffuse to UCN guide / storage volume

acceleration

UCN average velocity 5m/s
\( (v_{av}/4) \cdot 24\text{ms} = 3 \text{ cm} \)

Superfluid He, \( \varepsilon \sim 100\% \)
SD2, \( \varepsilon \sim 10\% \) [Phys.Rev.C71(2005)054601]

\( ^4\text{He} \)

scattering

UCN production

phonon

cold neutron

absorption

\( \gamma \) heating

quickly removed

neutron capture \( \gamma \)
Shuttered UCN source

- **exp. bottle**
- **UCN valve**
- **shutter**
- **phonon**
- **UCN**
- **SD2**
- **neutron temperature**

- UCN 3 mK
- 20~80 K cold moderator
- 300 K thermal moderator
- few $10^{10}$ K

- neutron evaporation from spallation product
## World's UCN projects, $\rho_{\text{UCN}} = P_{\text{UCN}} \times T_s \times \varepsilon_{\text{ext}} \times \text{(dilution factor)}$

<table>
<thead>
<tr>
<th>Source</th>
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<th>$E_c$ (neV)</th>
<th>$P_{\text{UCN}}$ (cm$^3$/s)</th>
<th>$T_s$ (s)</th>
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Present status

Los Alamos 76 kW:
\[ \rho_{\text{UCN}} = 145 \text{ UCN/cm}^3 \text{ in a 3.6 liter bottle at } E_c = 200 \text{ neV} \]
\[ 0.8 \text{ UCN/cm}^3 \text{ at experiment} \]

PSI 1.2 MW: will start in 2009

Munich 100 kW Trigger reactor at Mainz:
\[ 8 \text{ UCN/cm}^3 \text{ in a 10 liter bottle at } E_c = 250 \text{ neV} \]

Sussex-RAL 60MW:
\[ P_{\text{UCN}} = 1 \text{ UCN/cm}^3/\text{s at } E_c = 250 \text{ neV} \]

Ours 390 W:
\[ P_{\text{UCN}} = 4 \text{ UCN/cm}^3/\text{s in a 10-liter He-II at } E_c = 210 \text{ neV} \]
\[ (\rho_{\text{UCN}} = 160 \text{ UCN/cm}^3 \text{ at } \tau_s = 40 \text{ s}) \]
\[ \rho_{\text{UCN}} = 10 \text{ UCN/cm}^3 \text{ at experimental port of } E_c = 90 \text{ neV} \]
UCN production in our prototype source

UCN detector

SUS disk with a 1-cm diam hole

open

UCN valve

UCN guide

3 m

To $^4$He pump

To $^3$He pump

UCN

phonon

He-T

19 K $^2$H$_2$O

35 K

3He cryostat

Liq. He

1.25 m

SRD2

To pump

Graphite

Spallation target

UCN production in our prototype source
Result of Nov. 2006

UCN production with a proton-pulse of 1 μA

-proton

\[ \tau = 30 \text{ s at } T_{\text{He-II}} = 0.9K \]
With/without the annular SUS disk, with a p-pulse of 1μA

- UCN valve
  - closed
  - proton

With Al foil
- one shot counting
- UCN go back and forth
- Remove Al and the disk
UCN density by 390W p beam

$v_{av} = 3.1 \text{ m/s at } E_c = 90 \text{ neV}$

UCN flow rate = $\frac{1}{4} \cdot \rho v_{av} S$

count rate = $\frac{1}{4} \cdot \rho v_{av} S_d \cdot \epsilon = 409 \text{ counts/s}$

$\rho = 10 \text{ UCN/cm}^3$

assuming statistical distribution

$1.2 \times 10^6 \text{ UCN} / 36 \text{ liter}$

$1.2 \times 10^6 \text{ UCN/30 s for 10 liter He-II}$

production rate = $4 \text{ UCN/cm}^3/\text{s}$
Comparison with the theoretical prediction

Present exp. : production rate = 4 UCN/cm$^3$/s
5.2 UCN/cm$^3$/s ($E_c$: 210 → 250 neV)

4 ~ 8 UCN/cm$^3$/s at 400W, 250neV

Predicted production rate

\[ \frac{1}{8} \times (2 \sim 4) \times 10^{-9} \Phi_n /cm^3/s, \ \Phi_n(T_n = 80 \ K) \]
\[ \Phi_n = 1.5 \times 10^{10} (n/cm^2/s) \ by \ Monte \ Carlo \]

[ (2\sim4) \times 10^{-9} \Phi_n /cm^3/s, \ \Phi_n(T_n = 20 \ K) ]
Heating is transformed to $^3$He gas kinetic energy latent heat (potential energy) $= 34.5$ J/mol at 0.8 K

$^3$He gas flow $\propto \gamma$ heating
γ heating in He-II
at a 390W of proton beam

$^3$He gas flow increased by 0.8 slm
\[ \gamma \text{ heating} = 20 \text{ mW} \]
He-temperature increased by 0.01 K
\[ \uparrow \]
75 mW
by Monte Carlo assuming D$_2$O is an ideal gas

Neutron temperature expected to be higher, 20 K → 80 K
neutron capture rate may be smaller at higher temperature
or Bragg cut off?
Cooling power for He-II

latent heat of vaporization (34.5 J/mol) × \(P_{He}\) (vapor pressure 3 Torr at 0.8 K) × \(dV/dt\) (pumping power \(1\times10^4\) m\(^3\)/h) / \(R\) (gas constant)

17 W

\(\gamma\) heating is 8 W at 20 kW of p beam by Monte Carlo

\(^3\)He flow rate showed much smaller heating
Preparation for Ramsey resonance with the present source
Study of EDM cell

- Fomblin coated Teflon bottle
- UCN detector from UCN source
- Filling valve
- Emptying valve
- UCN spin analyzer (in preparation)
- UCN spin polarizer (in preparation)
- After t s
- H₀, E (in preparation)
- H₁ (in preparation)
- UCN count
Results of Nov. 2007

Storage time in the Teflon bottle: $\tau_s = 210$ s

- Filling valve closed
- Leak from emptying valve
- Emptying valve opened
- Opening time delayed
- More delay
- EDM can be measured

A proton pulse of 0.2 $\mu$A

Counts/Time bin/Cycle vs. Time (s)
Storage time measurement as a function of $h$

Fitting function:

$h = 30 \sim 90 \, \text{cm}$

$y = A \exp \left(-\frac{t}{\tau_1}\right)$

$h = 10 \sim 20 \, \text{cm}$

$y = A_1 \exp \left(-\frac{t}{\tau_1}\right) + A_2 \exp \left(-\frac{t}{\tau_2}\right)$

**Height Dependence of UCN Counts / SUS disk / $i_p=1 \, \mu A$ / Storage time measurement as a function of $h$**

- $\tau_1 = 23 \, \text{s}$
- $\tau_2 = 39 \, \text{s}$
- $h = 10 \, \text{cm}$
Ramsey resonance


\[ H_0 \cos \omega_0 t + H_1 \cos \omega_0 t = \omega_0 \]

\[ \Delta H_0 t = \pi \]

\[ \phi = \pi + \gamma \Delta H_0 t \cos \phi \]

\[ \gamma H_1 t_r = \pi/2 \]

H_1 rotations and Larmor precession are coherent

\[ H_1 \cdot x \cdot \cos \omega t_r + H_1 \cdot y \cdot \sin \omega t_r \]

\[ \omega = \omega_0 \]
\[ \varphi = \pi + \gamma \Delta H_0 \]
Experiment with prototype source

1. UCN density is consistent with the prediction.
2. We can remove the $\gamma$ heating, which is not so serious.
3. Storage time $T_s = 30$ s (improved to 40 s in Nov. 2007) is limited by the wall loss, but much longer in He-II bottle.
4. We are preparing Ramsey resonance with the present source.
At TRIUMF

$E_p \times I_p = 20$ kW

$\Phi_n = 1.8 \times 10^{12} \text{ /cm}^2\text{/s in 10L He-II}$

$P_{UCN} = 0.4 \times 10^4 \text{ UCN/cm}^3\text{/s}$

$E_c = 210 \text{ neV}$

$T_s = 150 \text{ s}$
The equation for UCN flux ($\rho_{UCN}$) is:

$$\rho_{UCN} = P_{UCN} \times T_s \times \varepsilon_{ext} \times (\text{dilution factor})$$

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