Problem of UCN anomalous losses and proposed solution

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and colleagues
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(some of experiments have been carried out in collaboration with JINR, ILL, and PSI)

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Temperature dependence of UCN loss factor $\eta$ for different beryllium traps

V.P. Alfimenkov et al., JETP Lett. 55 (1992) 84

1 – spherical deposited Be trap, not degassed;
2 – cylindrical deposited Be trap, degassed (5 hours at 250ºC);
3 – whole Be trap, degassed (8 hours at 300ºC);
4 – spherical deposited Be trap degassed (28 hours at 350ºC with purification of the evaporated He and D$_2$);
5 – theoretical temperature dependence calculated in the Debye model
**Low energy upscattering of UCN**
*(table of results)*

<table>
<thead>
<tr>
<th>Material</th>
<th>$\beta$ [per collision]</th>
<th>Upper limit 90% C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be coating of the gravitational spectrometer</td>
<td>(-4.7±2.3)⋅10^{-8}</td>
<td>&lt; 3.8⋅10^{-8}</td>
</tr>
<tr>
<td>Be foil</td>
<td>(2.2±1.6)⋅10^{-8}</td>
<td>&lt; 4.8⋅10^{-8}</td>
</tr>
<tr>
<td>Be coating of copper rings + Be foil</td>
<td>(1.1±1.3)⋅10^{-8}</td>
<td>&lt; 3.2⋅10^{-8}</td>
</tr>
<tr>
<td>Be weighted average</td>
<td>(0.5±0.9)⋅10^{-8}</td>
<td>&lt; 2.6⋅10^{-8}</td>
</tr>
<tr>
<td>Stainless steel (non-magnetic)</td>
<td>(-1.6±3.9)⋅10^{-8}</td>
<td>&lt; 6.4⋅10^{-8}</td>
</tr>
<tr>
<td>Cu (99.9 %)</td>
<td>(-1.9±2.2)⋅10^{-8}</td>
<td>&lt; 3.6⋅10^{-8}</td>
</tr>
<tr>
<td>Graphite coating</td>
<td>(1.7±0.8)⋅10^{-8}</td>
<td>&lt; 3⋅10^{-8}</td>
</tr>
<tr>
<td>Stainless steel (weak-magnetic)</td>
<td>(0.1±1.9)⋅10^{-8}</td>
<td>&lt; 3.2⋅10^{-8}</td>
</tr>
<tr>
<td>Fomblin</td>
<td>(5.0±0.1)⋅10^{-6}</td>
<td>(-4.7±2.3)⋅10^{-8}</td>
</tr>
<tr>
<td>Stainless steel [3] in the Earth magnetic field</td>
<td>(4.1±0.4)⋅10^{-7}</td>
<td>(-1.9±2.2)⋅10^{-8}</td>
</tr>
<tr>
<td>Stainless steel [3] in a magnetic field of 100-300 Oe</td>
<td>(1.2±0.6)⋅10^{-7}</td>
<td>(-1.9±2.2)⋅10^{-8}</td>
</tr>
<tr>
<td>Stainless steel [3] (after etching with HCl)</td>
<td>(1.2±0.5)⋅10^{-7}</td>
<td>(1.2±0.6)⋅10^{-7}</td>
</tr>
<tr>
<td>Be coating of the gravitational spectrometer (2005)</td>
<td>(2.2±0.2)⋅10^{-8}</td>
<td>(2.2±0.2)⋅10^{-8}</td>
</tr>
</tbody>
</table>

**Conclusion:** the low energy upscattering of UCN can not explain the UCN anomalous losses ($10^{-8} << 10^{-5}$)
Depolarization of UCN during their storage in material bottles (results)

<table>
<thead>
<tr>
<th>Material</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trap coating (Be) I (measurement in 1998)</td>
<td>$(0,72\pm0,07)\times10^{-5}$</td>
</tr>
<tr>
<td>Trap coating (Be) II</td>
<td>$(2,07\pm0,05)\times10^{-5}$</td>
</tr>
<tr>
<td>Be foil (measurements of 1998)</td>
<td>$(1,58\pm0,20)\times10^{-5}$</td>
</tr>
<tr>
<td>Be foil (measurements of 2000)</td>
<td>$(2,17\pm0,21)\times10^{-5}$</td>
</tr>
<tr>
<td>Be coating on copper rings</td>
<td>$(1,15\pm0,09)\times10^{-5}$</td>
</tr>
<tr>
<td>Be coating on Al foil</td>
<td>$(1,23\pm0,21)\times10^{-5}$</td>
</tr>
<tr>
<td>BeO coating on copper rings</td>
<td>$(3,75\pm0,33)\times10^{-5}$</td>
</tr>
</tbody>
</table>

The process of UCN reflection is not completely coherent.
Possible relation between UCN depolarization and UCN anomalous losses

coherent scattering

UCN depolarization

UCN anomalous losses

incoherent scattering
The temperature dependence of the macroscopic cross-section ($\Sigma$) for extruded beryllium ($\Delta$), quasi-monocrystal beryllium ($\Omega$), fused beryllium (+). The macroscopic capture cross-section for Be nuclei $\Sigma_a^{Be}=\rho^{Be}\cdot\sigma_a^{Be}$ is shown by a straight line.

It is very probable that defects (or defects with hydrogen) are the source of incoherent scattering.
Studies of UCN transmission through Be samples and Be coatings


Transmission through Be coating

UCN energy ($E_0$), neV

Transmission through Be coating

Probability for UCN to find defect on the surface $\sim (4\div6)\cdot10^{-5}$. 

$E_c^{Be}$ is the critical energy for UCN reflection on Be.

* twice coated on the same side with the cleaning of surface with alcohol after the first coating.
Main relations for normal UCN reflection losses

\[
\left( \nabla^2 + \frac{2m}{\hbar^2} E_0 \right) \psi(r) = \frac{2m}{\hbar^2} V(r) \psi(r)
\]

\[
V(r) = \sum_i \frac{2\pi \hbar^2}{m} b_i \cdot \delta(r - r_i)
\]

\[
U = \frac{2\pi \hbar^2}{m} \rho \text{Re} b
\]

\[
W = \frac{2\pi \hbar^2}{m} \rho \text{Im} b
\]

\[
|\psi(z)|^2 = Ce^{-2\alpha' z}
\]

\[
k_0 = \frac{1}{\hbar} \sqrt{2mE_0}
\]

\[
\alpha = \frac{1}{\hbar} \sqrt{2m(U - E_0 - iW)} \equiv \alpha' - i\alpha''
\]

\[
\alpha'' \approx \frac{W}{2\hbar \sqrt{U - E_0}}
\]

\[
\alpha'' = \frac{2\pi \rho \text{Im} b}{\alpha'}
\]
Main relations for normal UCN reflection losses

\[ R = \left| \frac{k_0 - k}{k_0 + k} \right|^2 \]

\[ \mu = 1 - R = 2\eta \sqrt{E_0 / (U - E_0)} \]

\[ \eta = \text{Im} b / \text{Re} b \]

\[ \sigma_{\text{tot.}} = \frac{4\pi}{k_0} \text{Im} b \]

\[ \mu = 2\sigma_{\text{tot.}} \rho \hat{\lambda} \frac{E_0}{U} \], where \( \hat{\lambda} = \frac{\hbar}{\sqrt{2m(U - E_0)}} \)

\[ \sigma_{\text{tot.}} = \sigma_{\text{incoher.}} + \sigma_{\text{capture}} + \sigma_{\text{inelastic scatt.}} + \sigma_{\text{elastic scatt.}} \]
Interaction of VCN and UCN with defects of material


\[
\left( \nabla^2 + \frac{2m}{\hbar^2} E_0 \right) \psi(r) = \frac{2m}{\hbar^2} V(r)\psi(r)
\]

\[V(r) = U - iW + \frac{2\pi\hbar^2 B}{m} \delta(r)\]

\[B = nb\]

\[
\psi = e^{ikr} + F \cdot \frac{e^{ikr}}{r}
\]

\[E_0 > U \quad G(r, r') = -\frac{1}{4\pi} \frac{e^{ik|r-r'|}}{|r - r'|}\]

\[
\psi = e^{\alpha z_0} \left( e^{-\alpha z} + F \cdot \frac{e^{-\alpha r}}{r} \right)
\]

\[E_0 < U \quad G(r, r') = -\frac{1}{4\pi} \frac{e^{-\alpha|r-r'|}}{|r - r'|}\]
Interaction of VCN and UCN with defects of material
(The capture cross-section on material defects)

probability density flux

\[ j = \frac{i\hbar}{2m} (\psi \nabla \psi^* - \psi^* \nabla \psi) \]

\[ E_0 > U \quad \psi = C e^{ikz} \]

\[ k = k' + ik'' \]

\[ j_{\text{incident}} = \frac{\hbar k'}{m} e^{-k''z} \]

\[ \sigma_{\text{capt.}} = -\frac{S}{j_{\text{incident}}} \int j r^2 d\Omega \]

\[ j_{\text{interf.}} = \frac{\hbar k''}{m} \text{Re} \left\{ \frac{2}{r^2} \left( F + \frac{1}{2ik} \right) \frac{1}{k^*} \right\} \]

\[ \psi \approx \frac{e^{ikr}}{r} \left( F + \frac{1}{2ik} \right) - \frac{1}{2ik} \frac{e^{-ikr}}{r} \]

- the contribution of the incoming wave

\[ j_{\text{in}} = -\frac{\hbar}{m} \frac{k'}{4|k|^2} \frac{e^{2k''r}}{r^2} \]

- the contribution of the outgoing wave

\[ j_{\text{out}} = \frac{\hbar k'}{m} \frac{e^{-2k''r}}{r^2} \left| F + \frac{1}{2ik} \right|^2 \]

- the contribution arising from the interference of the incoming and outgoing waves
\[ j_{\text{in}} = -\frac{\hbar k'}{m} \frac{e^{2k'r}}{r^2} \frac{1}{4|k|^2} \]

\[ j_{\text{out}} = \frac{\hbar k'}{m} \frac{e^{-2k'r}}{r^2} \frac{1}{4|k|^2} + \frac{\hbar k'}{m} \frac{e^{-2k'r}}{r^2} |F|^2 + \frac{\hbar k'}{m} \frac{e^{-2k'r}}{r^2} \frac{(F'k'' + F''k')}{|k|^2} \]

\[ j_{\text{interf}} = \frac{\hbar k''}{m} \frac{1}{r^2} \left( \frac{F'k'' - F''k'}{|k|^2} \right) \cos(2kr) - \sin(2kr) \left( \frac{F''k'' + F'k'}{|k|^2} - \frac{1}{2|k|^2} \right) \]

\[ \text{0} \]
Interaction of VCN and UCN with defects of material
(The capture cross-section on material defects)

Using the sum of the fluxes $j_{in}$, $j_{out}$ and $j_{interf}$ in the integral and taking the limit of $r$ equal to zero, one obtains the following formula for the absorption cross-section

$$E_0 > U \quad \sigma_{capt.} = 4\pi \left( \frac{\text{Im} F}{k'} - |F|^2 \right)$$

where $4\pi|F|^2$ is the elastic scattering cross-section.

$$\sigma_{tot.} = 4\pi \frac{\text{Im} F}{k'}$$

analog of the optical theorem for medium

$$E_0 < U \quad \sigma_{capt.} = 4\pi \left( \frac{\text{Im} F}{\varepsilon''} - |F|^2 \right)$$

$$\sigma_{tot.} = \frac{4\pi \text{Im} F}{\varepsilon''}$$

analog of the optical theorem for subbarrier scattering on the material defect

$$\sigma_{capt.} \bigg|_{E_0 < U} \approx \frac{|U - E_0|}{W} \sigma_{capt.} \bigg|_{E_0 > U} \quad k'/\varepsilon'' = \frac{E_0 - U}{W} \approx 10^4$$
Interaction of VCN and UCN with defects of material (conclusion)

\[ \sigma_{tot.} = \frac{4\pi \text{Im} F}{k'} \quad \sigma_{tot.} = \frac{4\pi \text{Im} F}{\varepsilon''} \]

\[ \varepsilon'' = \frac{2\pi\rho \text{Im} b}{\varepsilon'} \]

\[ \sigma_{tot.} = \frac{2\varepsilon' \text{Im} F}{\rho \text{Im} b} = \frac{2}{\lambda\rho} \frac{\text{Im} F}{\text{Im} b} \]
One-dimensional UCN source inside a substance

\[ \psi_1 = e^{-\alpha(d+z)} \]
\[ \psi_2 = A e^{\alpha z} \]
\[ \psi_3 = B e^{ikz} \]
\[ \psi_4 = C e^{\alpha z} \]

1. \( \psi_1 + \psi_2 = \psi_3 \bigg|_{z=0} \)
\[ e^{-\alpha d} + A = B \]

2. \( \psi_1' + \psi_2' = \psi_3' \bigg|_{z=0} \)
\[ -\alpha e^{-\alpha d} + \alpha A = ikB \]

3. \( \psi_1 + \psi_2 = \psi_4 \bigg|_{z=d} \)
\[ 1 + A e^{\alpha d} = Ce^{\alpha d} \]
\[ |\Psi_{(1+2)}|^2 = |F|^2 \ e^{-2\kappa'd} \ \left\{ e^{-2\kappa'z} + \frac{\kappa'^2 + (k - \kappa'')^2}{\kappa'^2 + (k + \kappa'')^2} e^{2\kappa'z} + \frac{\kappa'^2 - k^2 + \kappa''^2}{\kappa'^2 + (k + \kappa'')^2} \right\} \]

\[ = |F|^2 \ e^{-2\kappa'd} \ \left\{ 2\kappa'' \left( e^{-2\kappa'z} - \frac{\kappa'^2 + (k - \kappa'')^2}{\kappa'^2 + (k + \kappa'')^2} e^{2\kappa'z} \right) + 4\kappa' \left\{ \frac{\kappa'^2 - (k - \kappa'')^2}{\kappa'^2 + (k + \kappa'')^2} \sin(2\kappa''z) + 2 \frac{\kappa'k}{\kappa'^2 + (k + \kappa'')^2} \cos(2\kappa''z) \right\} \right\} \]

\[ = 8k |\Psi_{(3)}|^2 = |F|^2 \ e^{-2\kappa'd} \ \left\{ 8(\kappa'^2 + \kappa''^2) \right\} \frac{\kappa'^2 + \kappa''^2}{\kappa'^2 + (k + \kappa'')^2} k \]
One-dimensional UCN source inside a substance
(Solution: $|\psi|^2$ and $j$ as function of the source distance from surface)

\[ \frac{j_3(d)}{j_3(d=0)} = e^{-2\alpha'd} \]
\[ \frac{j_3(d)}{j_3(d=0)} = e^{-\rho \sigma d} \]

\[ \sigma = \frac{2\alpha'}{\rho} = \frac{2}{\lambda \rho} \]
\[ \alpha' = \frac{2\pi \rho \text{Im} b}{\alpha''} \]
\[ \sigma = \frac{4\pi \text{Im} b}{\alpha''} \]

$E_n = 60$ neV
$U = 220$ neV
$W = 10^{-6}U$
Formula for UCN anomalous losses and connection with UCN depolarization

\[ \mu_{an} \sim N_{def} \sigma_{an} l_{eff} \]

\[ \mu_{an} = N_{def} \int_{0}^{\infty} |\psi_0|^2 \sigma_{an} [1 - \delta(z)] dz \]

\[ \mu_{an} = N_{def} \sigma_{an} \frac{2E}{U} (1 - \frac{1}{4}) \]

UCN anomalous losses:

\[ \mu_{an} = \frac{N_{def} n \text{ Im } f}{\rho \text{ Im } b} \frac{4E}{U} (1 - \frac{1}{4}) \]

UCN depolarization:

\[ \alpha_{\text{spin–flip}} = \frac{N_{def} n \text{ Im } f}{\rho \text{ Im } b} \frac{4E}{U} \frac{1}{4} \]

\[ l_{eff} = \int_{0}^{\infty} |\psi|^2 dz \]

\[ \sigma = \sigma_{an} [1 - \delta(z)] \]

\[ \delta(z) = \frac{1}{2} e^{-2w'z} \]

\[ \sigma_{an} = \frac{2}{\frac{\text{ Im } F}{\frac{\text{ Im } b}{\lambda \rho} \frac{\text{ Im } f}{\lambda \rho \text{ Im } b}}} \]

\[ N_{def} - \text{ density of defects} \]
\[ \rho - \text{ density of substance} \]
\[ n - \text{ number of incoherent scattering centers inside defect (H)} \]
\[ b - \text{ scattering length of atom of substance} \]
\[ f - \text{ scattering length of incoherent scattering center (H)} \]
Estimation of losses in reflection from Be

\[ \mu_{an} = 2 \sigma_{an} N_{def.} \frac{\lambda}{\kappa} \frac{E_0}{U} (1 - \frac{1}{4}) \]

1. \( L = ? \)
   \[ \downarrow \]
   \( 100 \, \text{Å} \)
   \( L \approx \lambda \)

\[ \sigma_{an} = \frac{4\pi \text{Im}(nb)}{\alpha''} = \frac{2n}{\lambda \rho} = 0.8 \cdot 10^{-12} \, \text{cm}^2 \]
\[ n = 0.5 \rho (100 \, \text{Å})^3 = 0.6 \cdot 10^5 \]

2. \( N_{def.} = ? \)
   \[ \Sigma = N_{def.} \sigma_{scatt.def.} = 1 \pm 2 \, \text{cm}^{-1} \]

\[ \sigma_{scatt.def.} = 4\pi (nb)^2 = 2.9 \cdot 10^{-14} \, \text{cm}^2 \]

\[ N_{def.} = \frac{\Sigma}{\sigma_{scatt.def.}} = 3.5 \div 7 \cdot 10^{13} \, \text{cm}^{-3} \]

\[ \mu_{an} = N_{def.} \frac{\sigma_{tot.def.}}{2} \frac{\lambda}{\rho} = \frac{N_{def.} n}{\rho} = (1.7 \div 3.4) \cdot 10^{-5} \]
Temperature independence of anomalous losses

\[ \sigma_{an} = \frac{4\pi \text{Im}(nb)}{\dot{\alpha}''} = \frac{2n}{\dot{\lambda}\rho} \]

\[ \sigma_{an} = \frac{4\pi \text{Im}(n_{Be} b_{Be} + n_{H_2} b_{H_2})}{\dot{\alpha}''} = \]

\[ = \frac{2}{\dot{\lambda}\rho} \left[ n_{Be} \frac{\text{Im} b_{Be}(T)}{\text{Im} b_{Be}(T)} + n_{H_2} \frac{\text{Im} b_{H_2}(T)}{\text{Im} b_{Be}(T)} \right] \]
Energy dependence of anomalous losses:

\[ \mu_{an} = 2\sigma_{an}N_{def}\hat{\lambda}\frac{E_0}{U}\left(1 - \frac{1}{4}\right) \]

\[ \sigma_{an} = \frac{4\pi \text{Im}(nb)}{\sigma''} = \frac{2n \text{Im} f}{\hat{\lambda}\rho \text{Im} b} \]

\[ \hat{\lambda} = \frac{\hbar}{\sqrt{2m(U - E_0)}} \]

Energy dependence of normal losses:

\[ \mu_n = 2\eta\sqrt{\frac{E_0}{U - E_0}} \]

Energy dependence of anomalous losses:

\[ \mu_{an} = \frac{3N_{def}nE_0}{\rho}\frac{\text{Im} f}{U \text{Im} b} \]
Conclusion

1. Experimental data shows that UCN anomalous losses cannot be explained in the context of neutron optics calculations.

2. Incoherent scattering on the material defects with hydrogen is considered as explanation of anomalous losses phenomenon.

3. The theoretical consideration shows that total cross-section of UCN interaction with defect of material is:

   \[ \sigma_{\text{tot.def.}} = \frac{4\pi \text{Im} F}{\alpha''} \quad \text{for subbarrier case } E_0 < U \]

   and

   \[ \sigma_{\text{tot.def.}} = \frac{4\pi \text{Im} F}{k'} \quad \text{for abovebarrier case } E_0 > U \]
Optical theorem has the same general form (1/ν law) but effective velocity is considerable different for subbarrier and abovebarrier cases.

4. Proposed theoretical consideration can explain:
   a) value of anomalous losses
   b) temperature independence of anomalous losses and enhancement of inelastic scattering
   c) energy dependence of anomalous losses
   d) depolarization of UCN at the reflection

It seems that long-standing problem of UCN anomalous losses is solved.