# Quasi-Elastic Wall Reflections of Ultracold Neutrons

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# 1. Motivation

- Measurement of $\tau_n$ requires a long storage lifetime of UCN
- Do reports of "small heating" and of "small cooling" mean: **quasi-elastic scattering of UCN?**
- Does quasi-elastic scattering explain (some of) the UCN "storage anomaly"?
- What are the prospects of "low-temperature Fomblin" for a new measurement of $\tau_n$?

# 2. Experiment looking for quasi-elastic UCN scattering with energy loss on Fomblin-grease coated wall

Principle:

Store UCN with energies in a narrow band and look for indication of down-scattering by a few neV

# SYSTEM 1

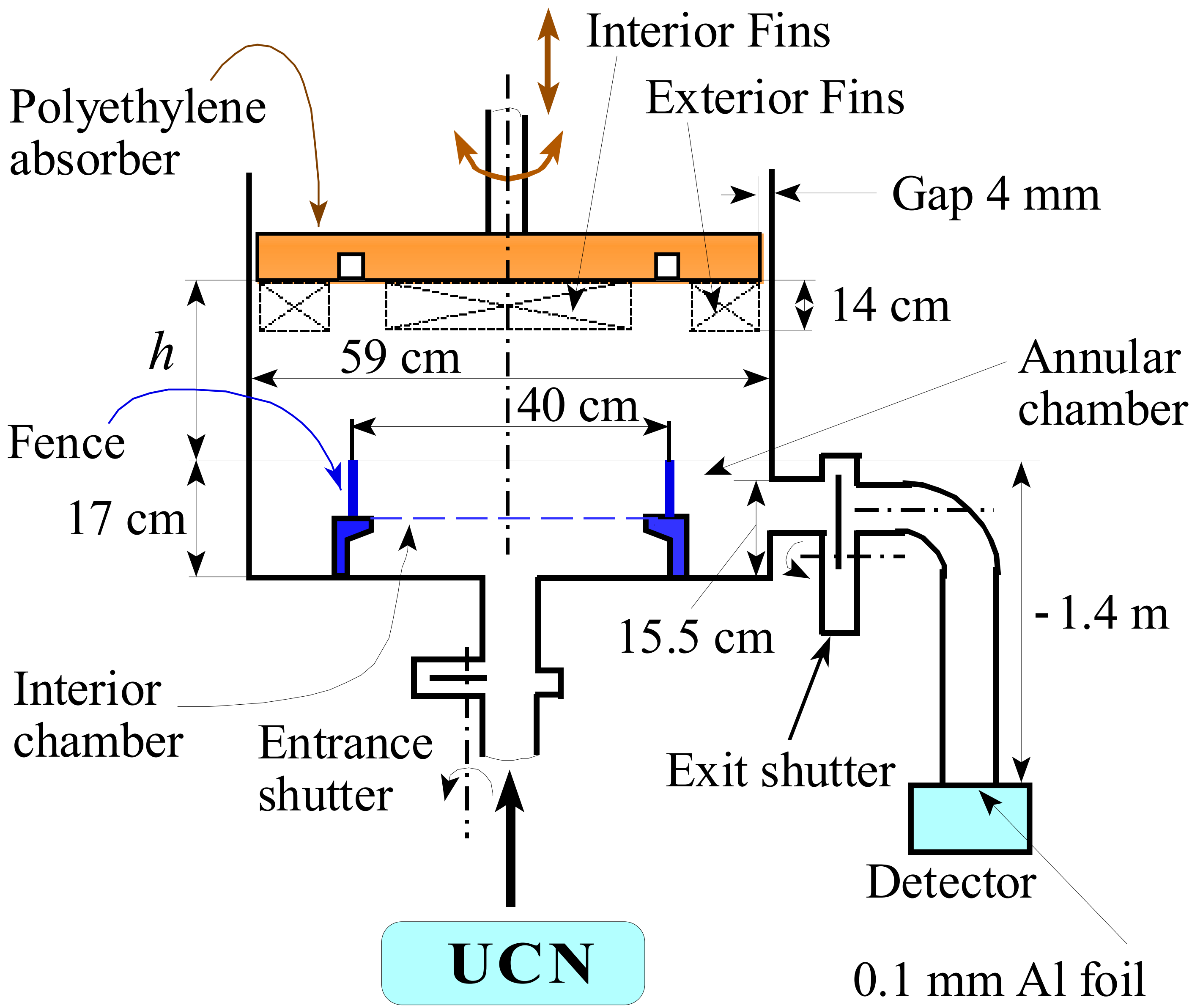


Fig. 1 System 1

## *Lower spectral cutoff*:

17 cm high gravitational hurdle ("fence")

## *Upper spectral cutoff*:

Rotating and movable PE absorber with extensions reaching almost to trap bottom; exterior extension is optional;

precision of vertical position is 0.01 mm

# *Typical measurement cycle*

- ***Trap loading***… for 50 – 170 s; absorber is at a high position $h_1$; exit shutter is closed (or no exit shutter is used)
- ***Fast UCN removal***… by lowering absorber below fence top ($h_0 < 0$); exit shutter opens (if used)
- ***Measuring phase*** … for 100 - 300 s with absorber at low position
- ***Absorber raised*** … again toward end of cycle

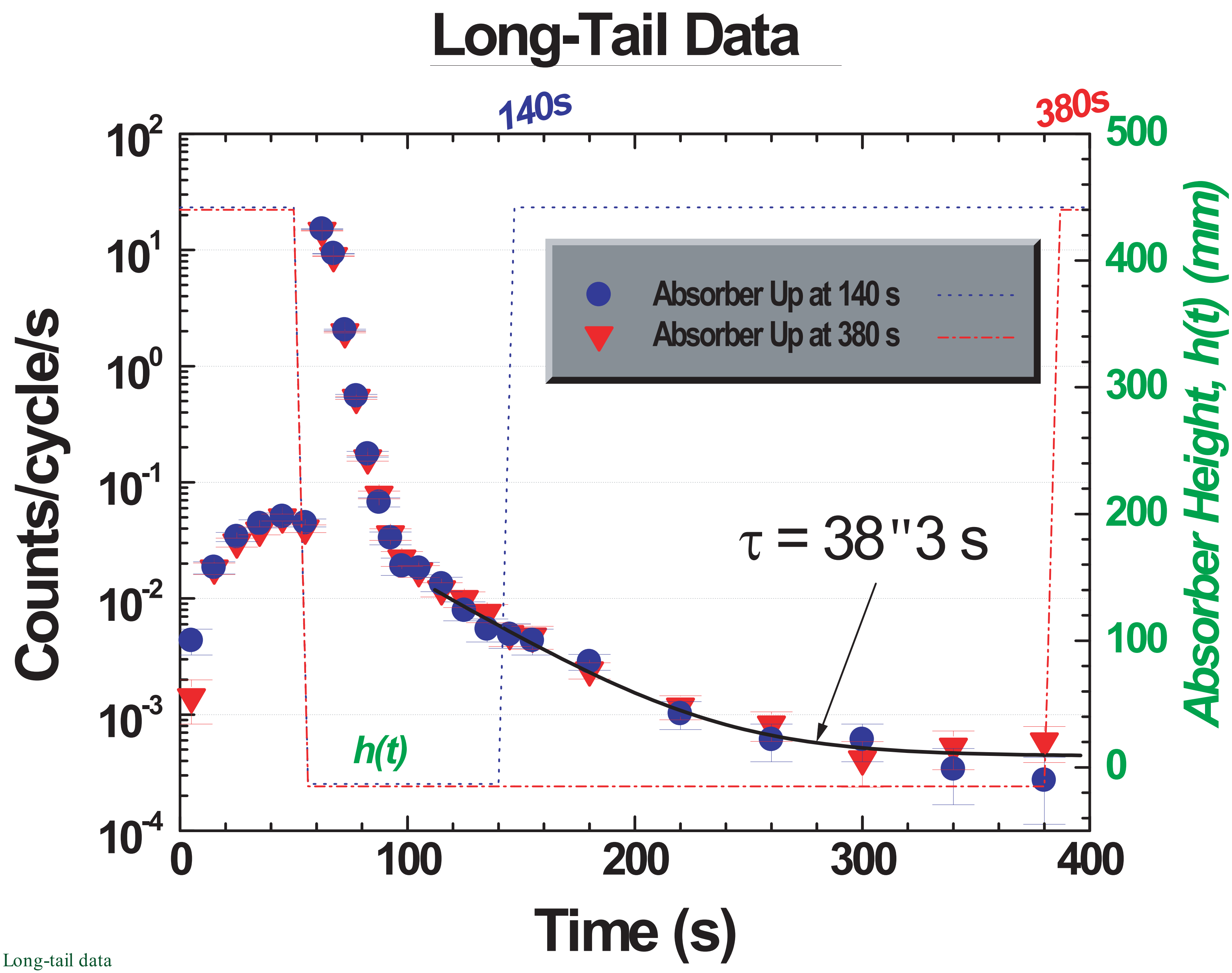


Fig. 2 Long-tail data

## *The "long tail":*

= Transition to a slow decrease of count-rate ($\tau \approx 40$ s);

No increase of count-rate when absorber I (without exterior extension) is raised again;

→ This shows that no faster UCN are left;

[But under the less efficient absorber II (with exterior extension), faster UCN survive quite long.]

Efflux time constant **$\tau \approx$ 40 s is much longer than** the value **21.7±0.5 s** measured for UCN with energy just enough to jump over the "fence".

**$\tau$ increases when the exit guide cross section *A* is constricted; from 40 s to 66 s for 1.6 times smaller *A*.**

# *Origin of the "long tail"* (most plausible explanation):

*Quasi-elastic down-scattering by a few neV* during trap loading (when the UCN density is high).

**For instance**: If UCN of 17 neV (just clearing the fence) are down-scattered by 4 neV, then they will no longer reach the upper 2.5 cm of the exit guide. Thus, the effective exit area and the velocity are reduced.

→ $\tau$ increases from ≈ 22 s to ≈ 40 s.

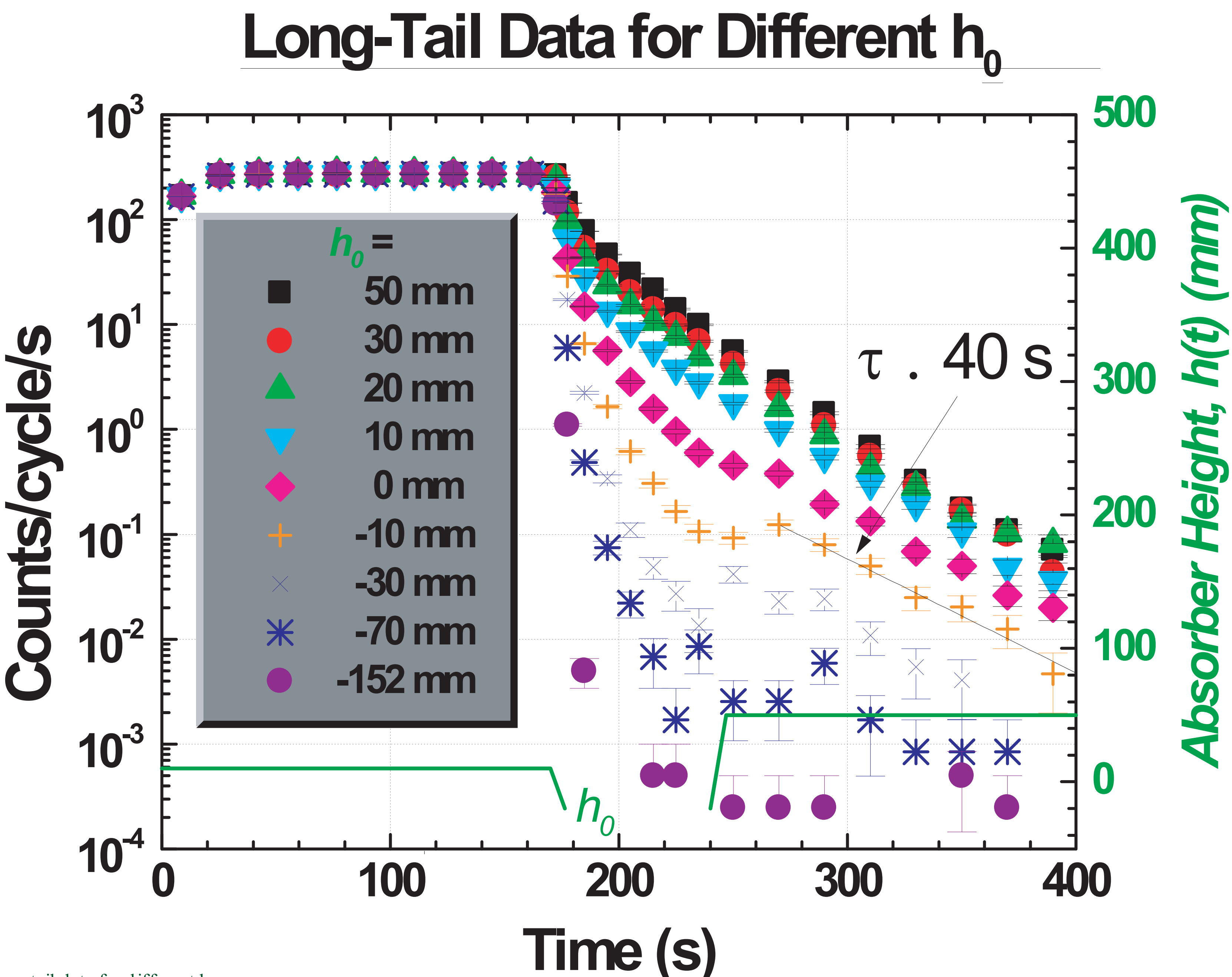


Fig. 3 Long-tail data for different $h_0$

Measurement of “long-tail” intensity as a function of $h_0$ (down to $h_0 \approx$ -10 cm) gives a decrease by a factor of two for $\Delta h_0 \approx$ -2 cm.

Measurement at $h_0$ = -15.2 cm (completely below the exit guide) gives zero “long-tail” intensity.

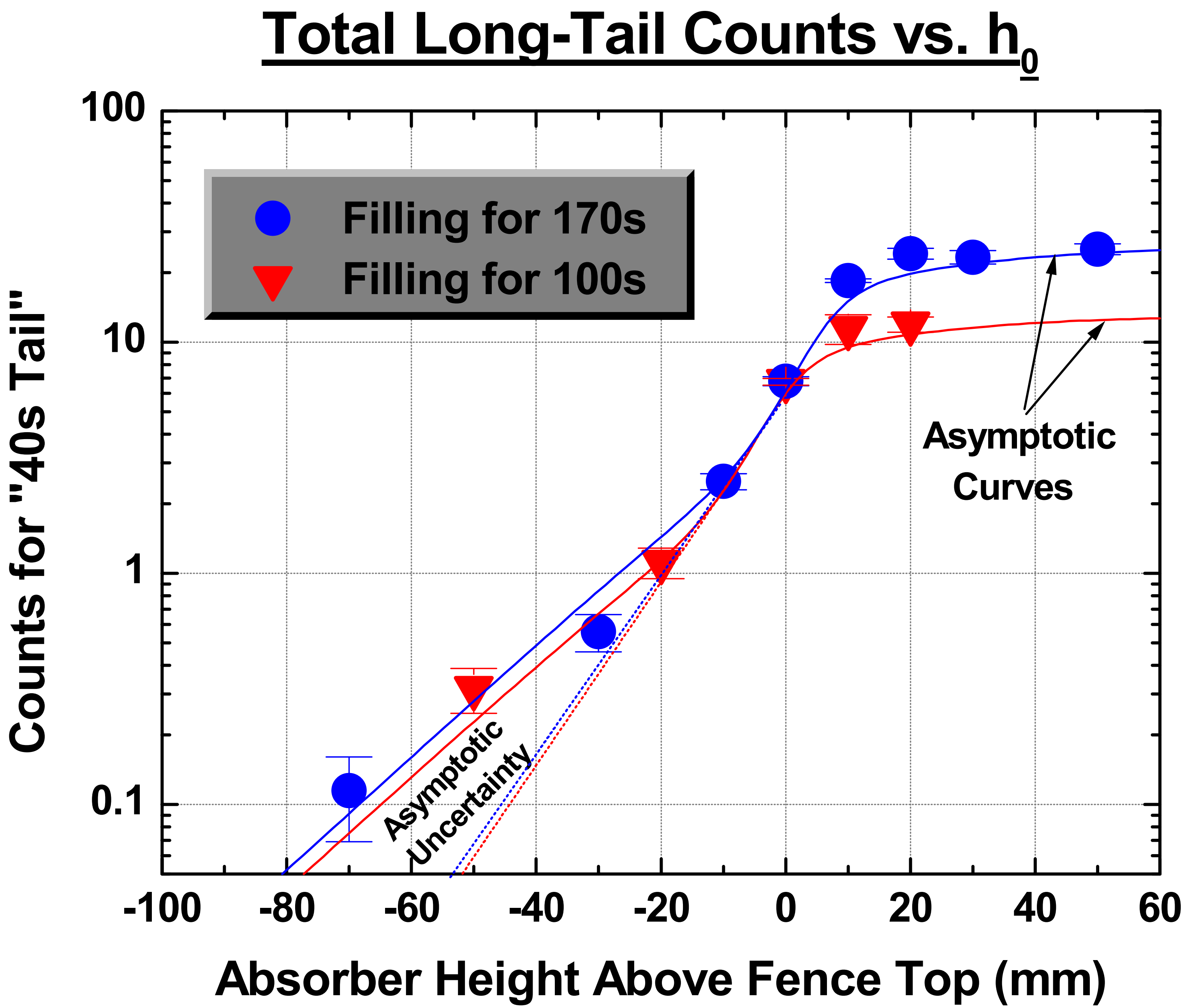


Fig. 4 Total long-tail counts vs. $h_0$

# *Estimate of quasi-elastic down-scattering probability*

Relate the integral “long-tail” intensity for $h_0$ = -15 mm (with good absorber) to net frequency of wall collisions during loading.

**Result for r.t. Fomblin grease**

(after calculation):

$$\boldsymbol{p_{\mathbf{down}} = 1.4\times10^{-6}} \text{ for } \Delta E \leq -4 \text{ neV}$$

**(within a factor of two)**

# 3. Experiment looking for quasi-elastic UCN scattering with energy gain on Fomblin grease and oil and on “Low Temperature Fomblin” (LTF)

Principle:

Store UCN with a sharp upper spectral cutoff energy $mgH$ and measure the transmission through a thin foil with scattering potential $V_c = mgH_c > mgH$

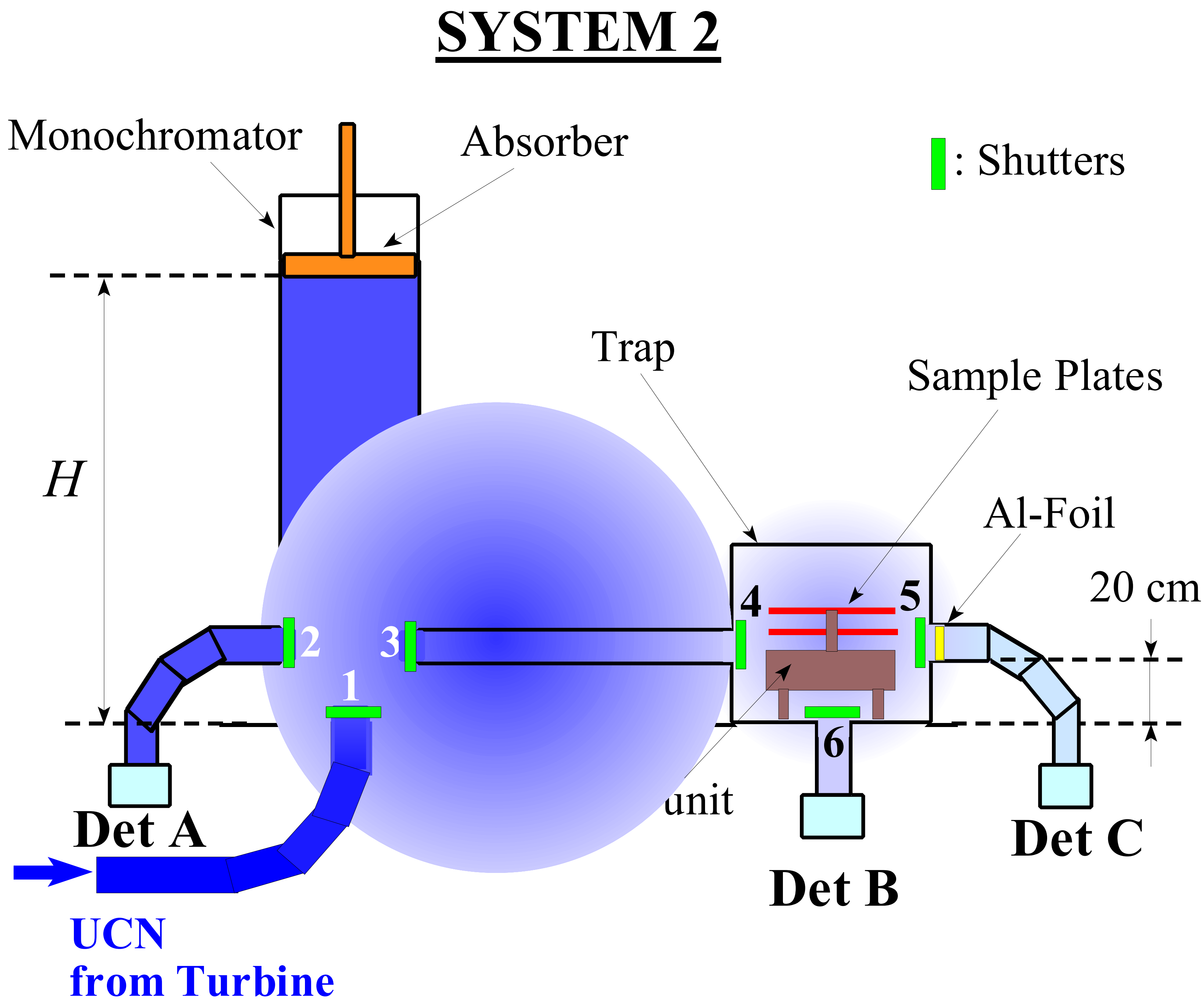


Fig. 5 System 2

## *Upper spectral cutoff:*

Achieved by long cleaning time (100 – 200 s) in low-loss Be-coated monochromator

# *Typical measurement cycle (with constant absorber height H)*

- ***Monochromator loading*** ...for 100 s
- ***Long spectral cleaning***... in monochromator
- ***UCN transfer*** ... (for 100 s) to UCN trap containing samples kept at $T = 160 – 300$ K
- ***Measurement*** ... of foil transmission and leakage current through shutter *6* for 100 – 600 s
- ***Emptying of trap*** ... (for 100 – 150 s) and measurement of total UCN count

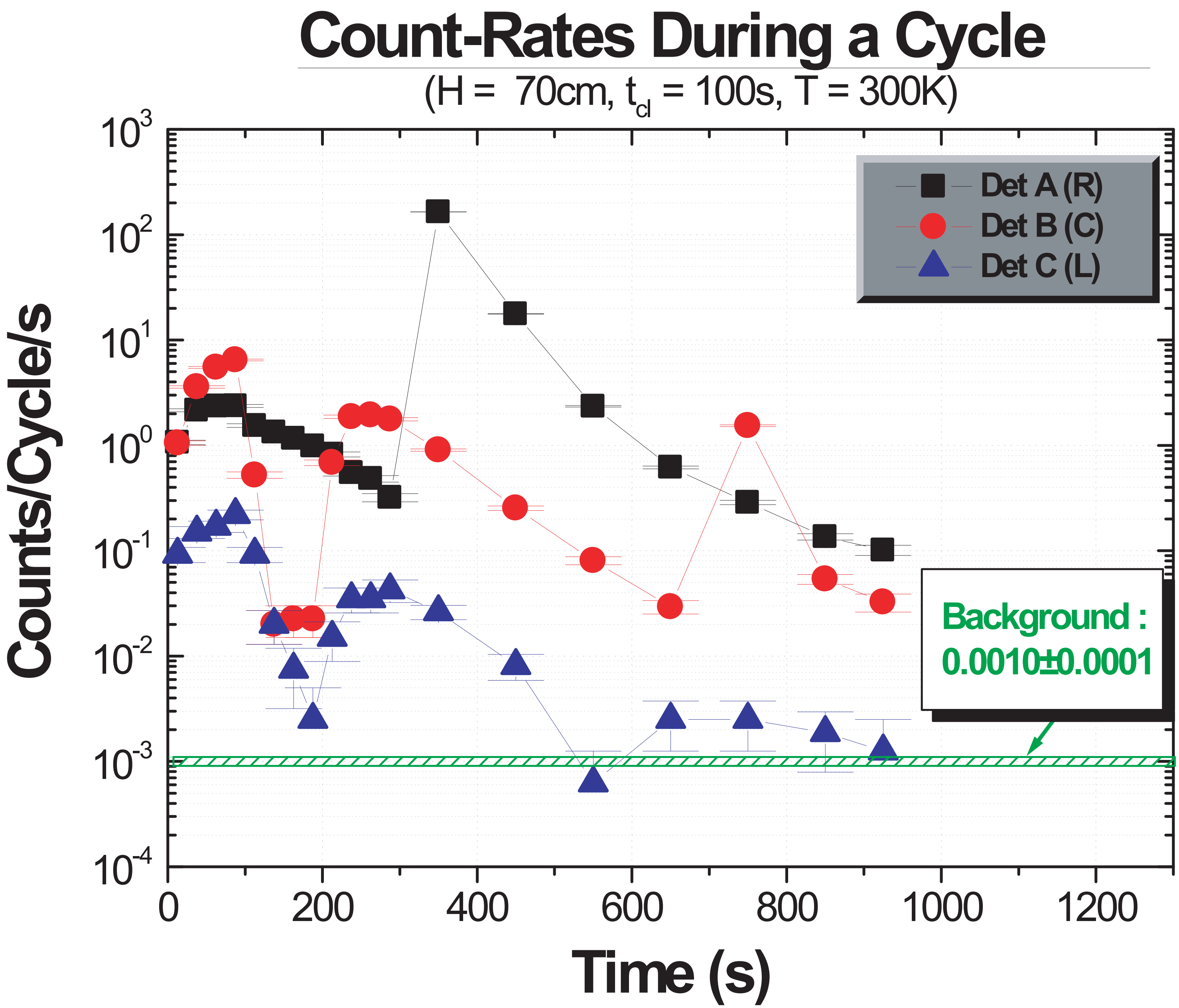


Fig. 6 Count-rates during a cycle

# Quasi-Elastic Reflectivity $p(H)$ and $p(T)$ for LTF1 and LTF2

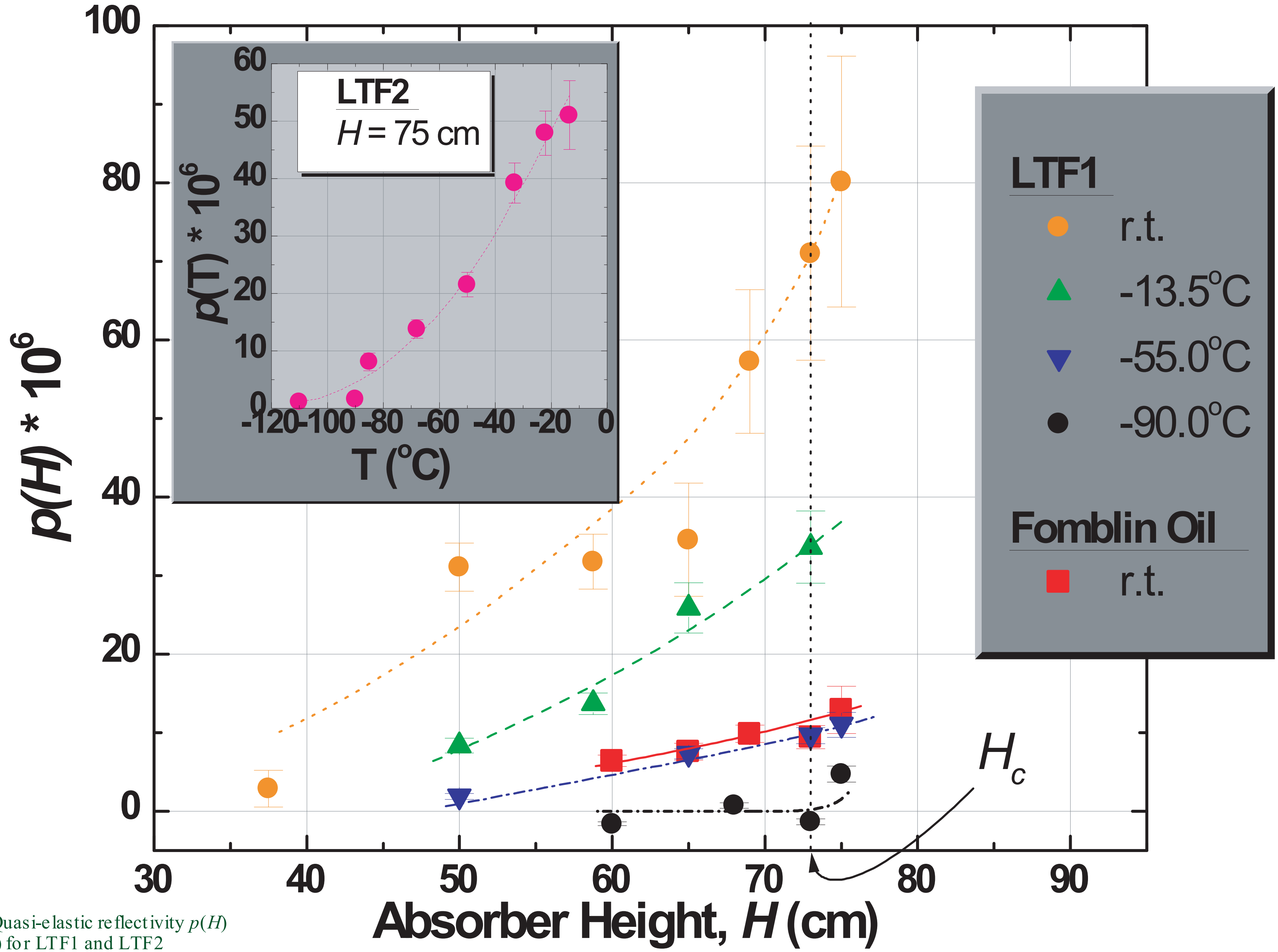


Fig. 7 Quasi-elastic reflectivity $p(H)$ and $p(T)$ for LTF1 and LTF2

# Samples

- Fomblin grease at room temperature
- Fomblin oil at r.t.
- LTF1 (mol. weight $M = 4883$, vapor pressure $P = 7\times10^{-5}$ mbar at r.t.) for $T = 180 - 300$ K
- LTF2 (mol. weight $M = 2354$, vapor pressure $P = 1.5\times10^{-3}$ mbar at r.t.) for $T = 160 - 300$ K

"***Low Temperature Fomblin*"** oils are ***Perfluoro Polymers***
e.g., PFPF (Perfluoro Polyformaldehyde) $C_4F_9(OCF_2)_nC_4F_9$ , $n = 6\text{-}10$ (Sung 1995)

Proposal of use for low-loss UCN traps: Pokotilovski, NIM A425 (1999) 320

# Physical Properties of LTF's:

- Wide fluid range: $T_{solid}$ = 121 - 128 K
  $T_{vapor}$ = 398 - 476 K
- $T_{solid}$ is ~100 K below Fomblin (≈ -40ºC) due to special bonding between $CF_3$ and $OCF_2$ groups.
- Density (1.8 g/cm$^3$) and Fermi potential similar to Fomblin

- Pokotilovski measured viscosity and $\sigma_{inel}$ (thermal) as a function of $T$. Relative to Fomblin oil, viscosity curves are shifted down by ~ 60 K.
- Vapor pressure: presumably low at low $T$
- $\sigma_{tot}(T)$: Data of Pokotilovski indicate low up-scattering losses at $T \leq 180$ K

# Analysis of quasi-elastic up-scattering data

Combine the various integral count-rates of detectors *B* and *C* with calibration and empty-trap background data to determine

$p(H,T)$ = probability of quasi-elastic up-scattering by $\Delta E \geq mg(H_c - H)$ for various values of temperature

# Main results

a) **At $T \leq 180$ K, $p$ is at least 3 times lower than for Fomblin oil at r.t.**

Compare to Pokotilovski's estimate:

$\sigma_{ie}(\text{r.t.})/\sigma_{ie}(-120^{o}\text{C}) \approx 5$

b) **For Fomblin grease at r.t.:**

$p_{up} = 3\times10^{-6}$ **for $\Delta E \rightarrow +0$ (small)**

This is comparable to $p_{down}$ :

$p_{down} = 1.4\times10^{-6}$ **for $\Delta E \leq -4$ neV**

(from the "long-tail" data)

c) **Decrease of $p_{up}$ by a factor of 2 for $\Delta E \sim 20$ neV**

# 4. Comparison with models

a) *Quasi-Elastic Scattering on Hydrogen Diffusing in Hydrogenous Impurity Layer on Fomblin Grease*

How much hydrogen on the surface is needed to explain the measured storage lifetime $\tau_{st} \approx$ 140 s ?

Neglecting the real part of potential, $\tau_{st}$ is determined by

- $n_H$ = # H-atoms/cm$^2$
- $\sigma_{loss} \approx$ 3300 b at v = 5 m/s

*Result*: $n_H = 8.1\times10^{16}$ cm$^{-2}$

($d$ = 12 nm for density of L-$H_2O$)

→ Mean loss/reflection: $\mu = 6.9\times10^{-4}$

Compare the probability $p_{down}$ of down-scattering to the "long tail" with the loss per reflection μ

$$r_{exp} = p_{down}/\mu = 0.0024$$

**Test of the model:** If the long-tail intensity and the reflection losses have the same origin (hydrogen on the surface), then the ratio $r_{\mathrm{exp}}$ should be the same as the cross section ratio for hydrogen

$$r_{\mathrm{model}} = \sigma_{\mathrm{qel}} / \sigma_{\mathrm{loss}}$$

# *Theory of quasi-elastic scattering on diffusing hydrogen (van Hove)*

$$d^2\sigma_{qel}/d\Omega d\omega = (\sigma_{inc}k/4\pi^2 k_0)\,[q^2D/(\omega^2 + q^4D^2)]$$

→ $d\sigma_{qel}/d\omega$ by integrating over $d\Omega$

*(Pokotilovski 1999); then integrate analytically over k from 0 to upper cutoff k:*

***Result:*** $\sigma_{qel}(x) = \sigma_{inc}F(x)$; $x = k/k_0$;

$\sigma_{inc} \approx 80$ b for H;

$F(x)$ depends on $b = 2mD/\hbar$;

$b = 0.057$ for $D_{\text{water, 300K}} =$

$1.8\times10^{-5}\ \text{cm}^2/\text{s}$

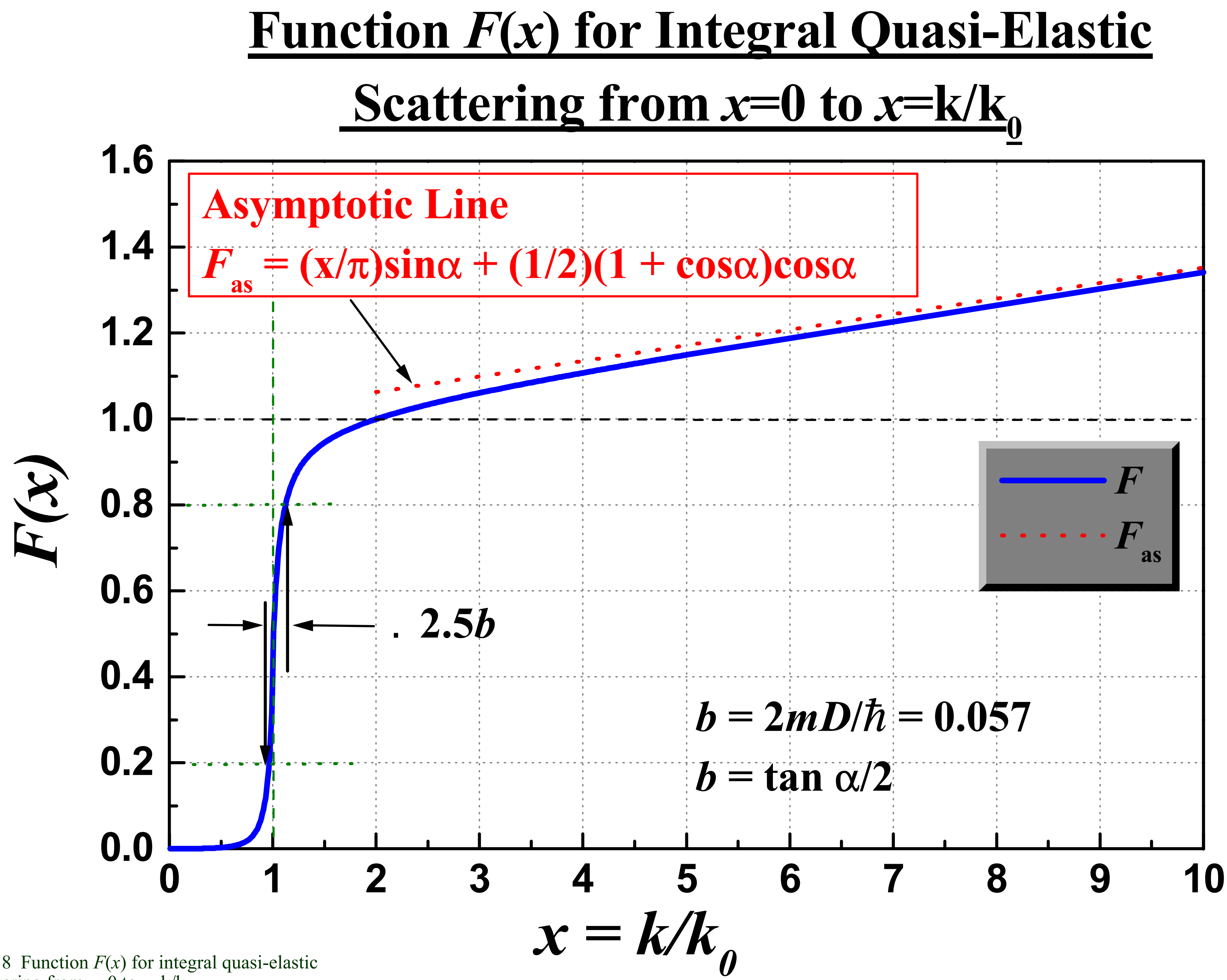


Fig. 8 Function $F(x)$ for integral quasi-elastic scattering from $x$=0 to $x$=k/k$_0$

## Features of *F(x)*:

- Typical quasi-elastic range: $(\Delta k)/k_0 \approx 2.5b$
- For $k_0 \rightarrow 0$: $\sigma_{qel}(x) \sim k_0^{-1}$ (like $\sigma_c$ and $\sigma_{ie}$)

Hence quasi-elastic UCN scattering on diffusing hydrogen atoms can be a significant source of UCN losses in traps.

# *Quasi-elastic down-scattering probability for hydrogen diffusing in a surface layer*

For $b = 0.057$:

$\tau \approx 40$ s corresponds to range $x \sim 0.62\text{-}0.95$;

$\Delta\sigma_{qel} = \sigma_{qel}(0.95) - \sigma_{qel}(0.62) \approx 13$ b;

Compare this to the mean loss cross section $\sigma_{loss} \approx 10700$ b for UCN spectrum in the trap

$$r_{\text{model}} = \Delta\sigma_{\text{qel}}/\sigma_{\text{loss}} = 0.0010$$

**Recall**

$$r_{\text{exp}} = p_{\text{down}}/\mu = 0.0024$$

**Agreement between $r_{\text{exp}}$ and $r_{\text{model}}$ within a factor of 2.5**

b) *Quasi-Elastic Scattering on Visco-Elastic Surface Waves at a Liquid Wall*

See theory of Pokotilovski, Phys. Lett. A255 (1999) 173

For quasi-elastic up-scattering tail, the measured decay (by a factor of two for $\Delta E \approx 20$ neV) is consistent with the analytical estimate.

# 5. Summary and Conclusions

- For Fomblin grease at r.t., both sides of quasi-elastic scattering (up and down) were measured; probabilities are similar ($\sim 10^{-6}$ per collision).
- Model of UCN scattering on hydrogen in a surface layer on the grease provides a consistent description of measured storage lifetime and of quasi-elastic down-scattering intensity ("long tail").

- Quasi-elastic up-scattering was also measured for liquid walls (Fomblin oil and two LTF's) for *T* in the range 160-300 K. Strong *T*-dependence and high-energy decrease by ~factor two per 20 neV are consistent with theory of quasi-elastic scattering on surface waves.
- LTF's are good candidates for new n-lifetime experiment at $T \leq 180$ K.
- Quasi-elastic UCN scattering may explain some UCN storage "anomalies".

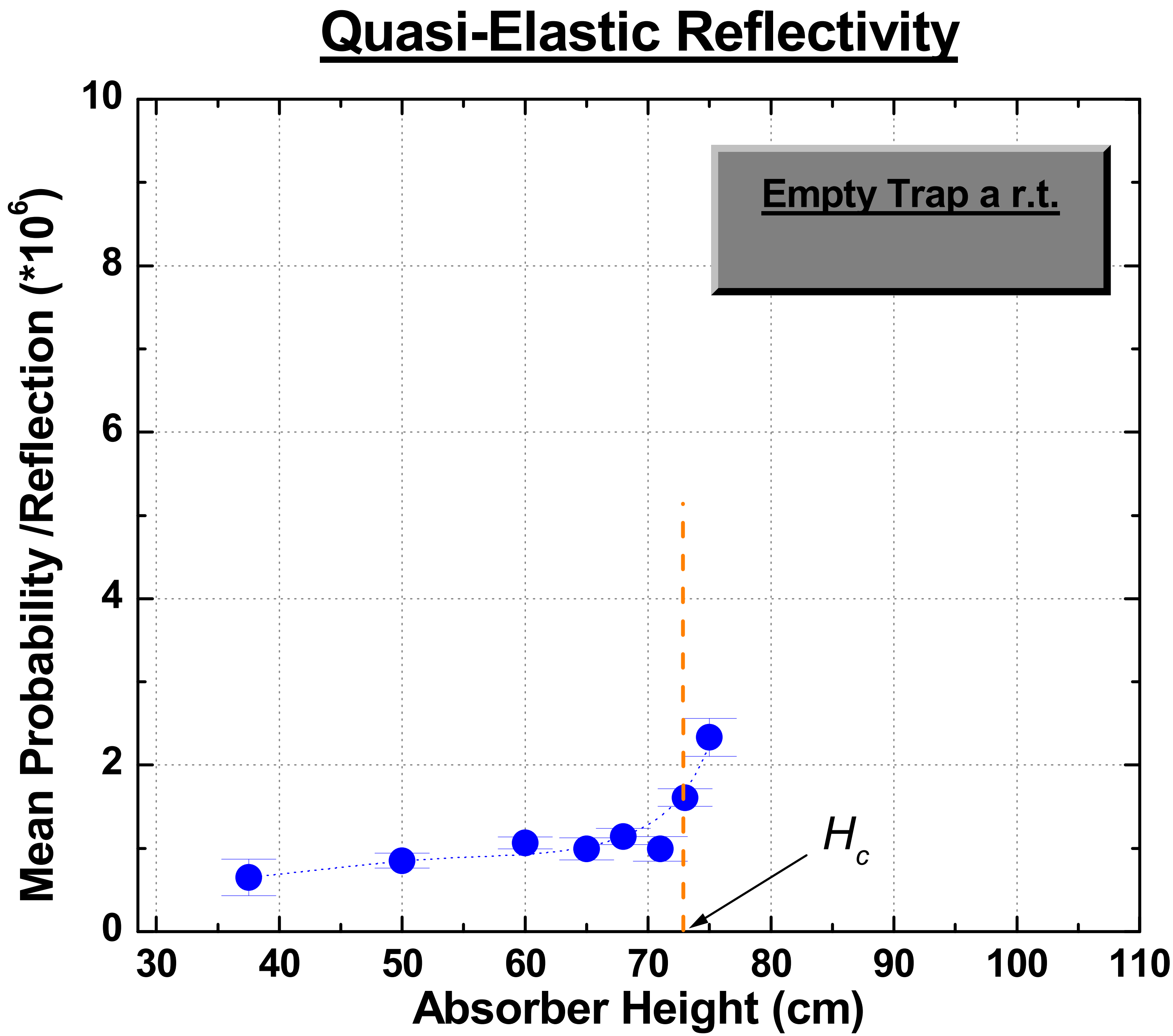


Fig. 9 Quasi-Elastic Reflectivity

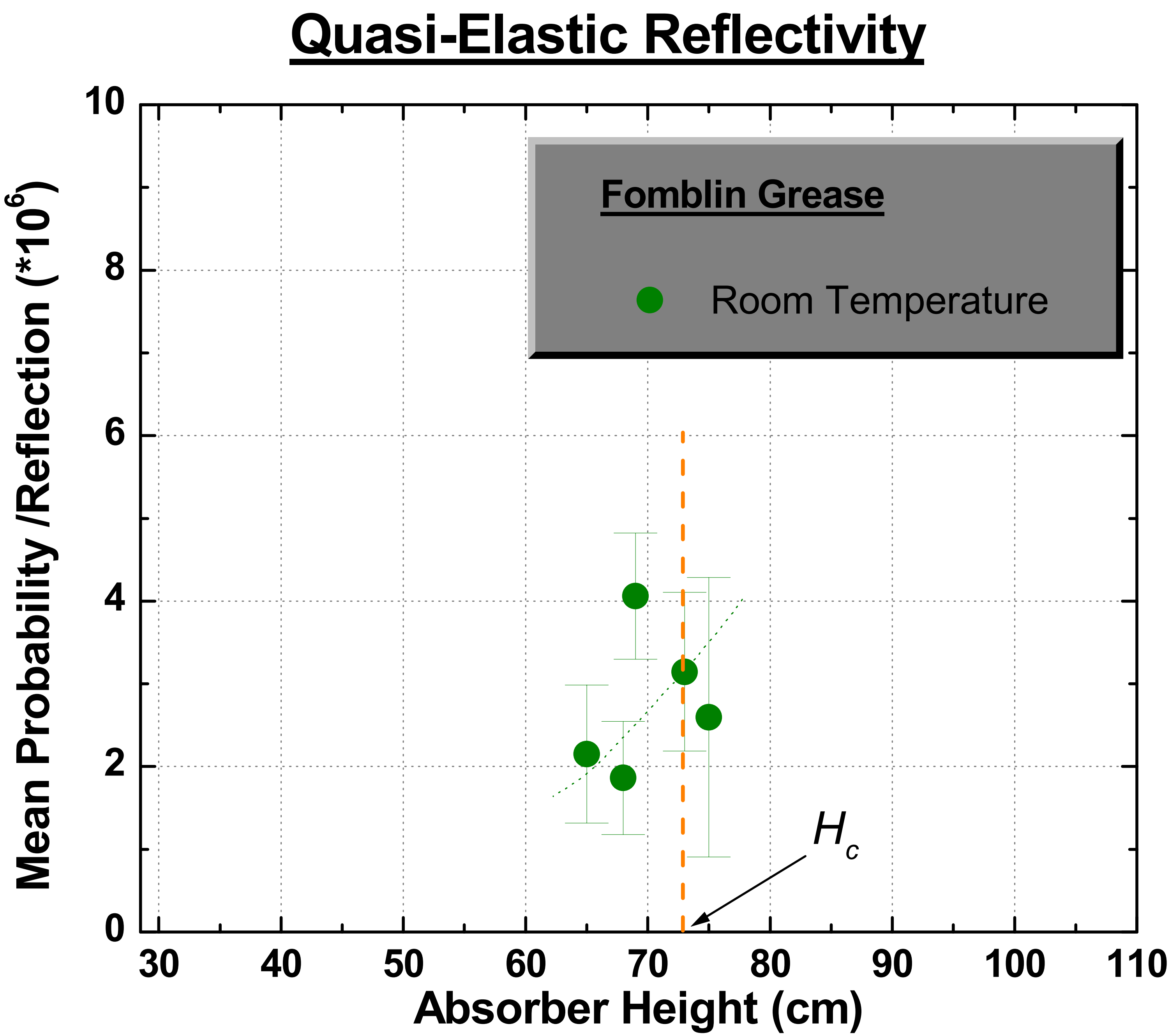


Fig. 10 Quasi-Elastic Reflectivity

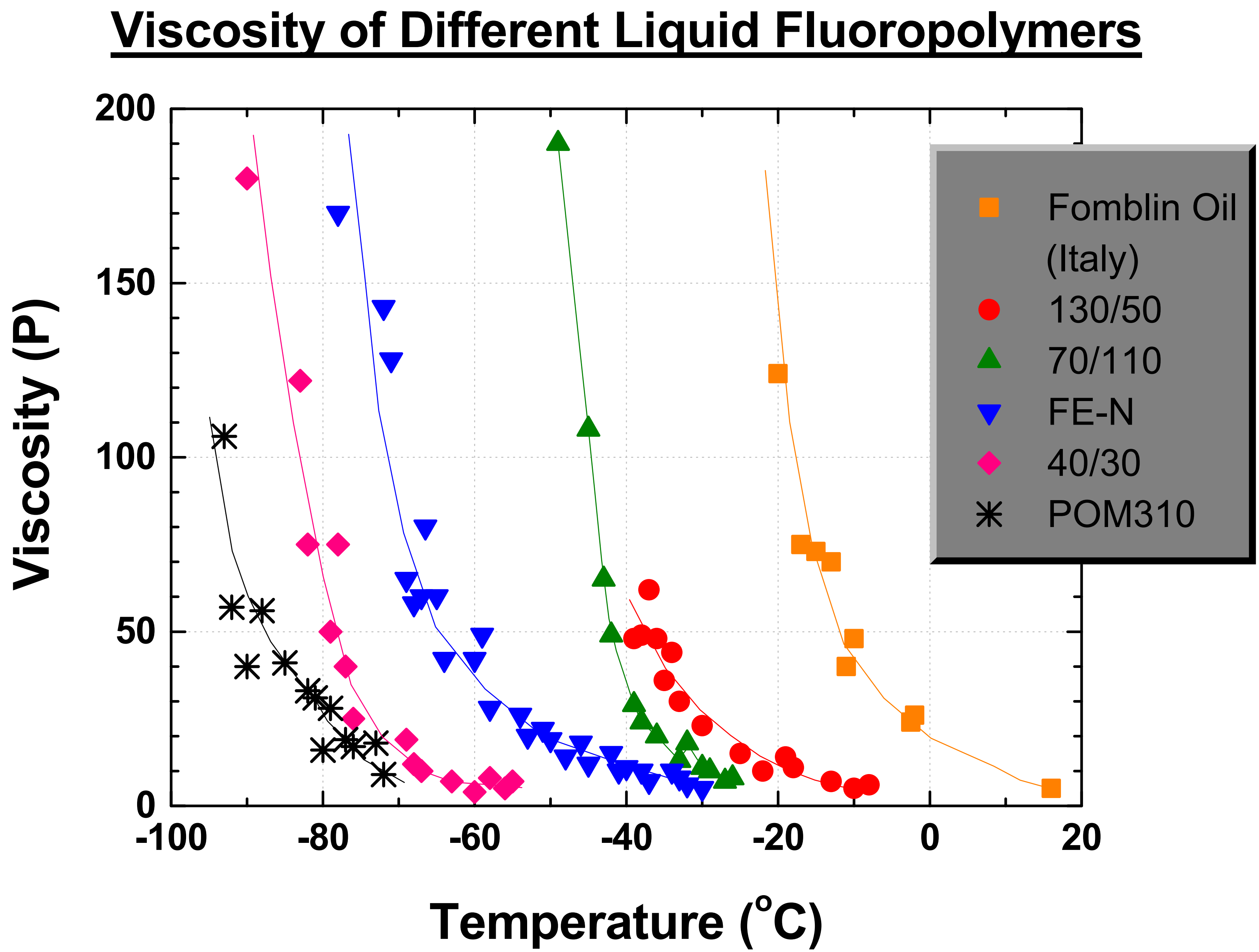


Fig. 11 Viscosity of Different Liquid Fluoropolymers