Hahn-Meitner-Institute

Condense matter physics with UCN

Dr. Ekaterina Korobkina

HMI hmi

- Inelastic interaction:

Non-destructive (UCN,prompt γ) analysis is sensitive to the

- Surface chemical content, especially Hydrogen
- inhomogeneities like clusters, porosity, pinholes, thin layers,

Study of UCN scattering on solids and liquids

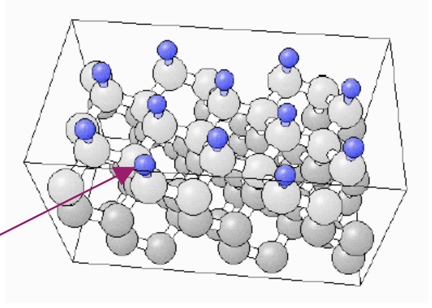
- UCN allowed us to measure with % accuracy the surface and bulk inelastic XS -advantage is that we don't need deuterated samples.
- Study of T-dependence of UCN upscattering at temperatures below 20K tells us about low energy excitations

- Elastic scattering
  - Anderson localization

Surface study with (UCN, gamma) analysis at low temperatures

- Measurement of both, H content (by gamma rays) and temperature dependence of the upscattering rate, tells about chemical bound of Hydrogen
  - Direct and tightly bound H undergoes acoustical vibrations of the lattice
  - Hydrogen from molecules usually is bound to Carbon or Oxygen that can be detected by much softer phonon spectrum
- UCN could be used to study origin of the "boson peak" - very low excitation commonly present at amorphous materials and polymers. The origin of the boson peak is not revealed yet. With high intensity UCN very thin layers of polymer could be studied.

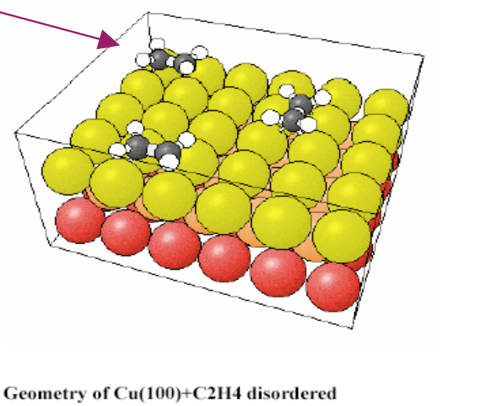
Picture from the NIST Surface Structure Database (SSD)*



Geometry of C(111)+(1x1)-H diamond

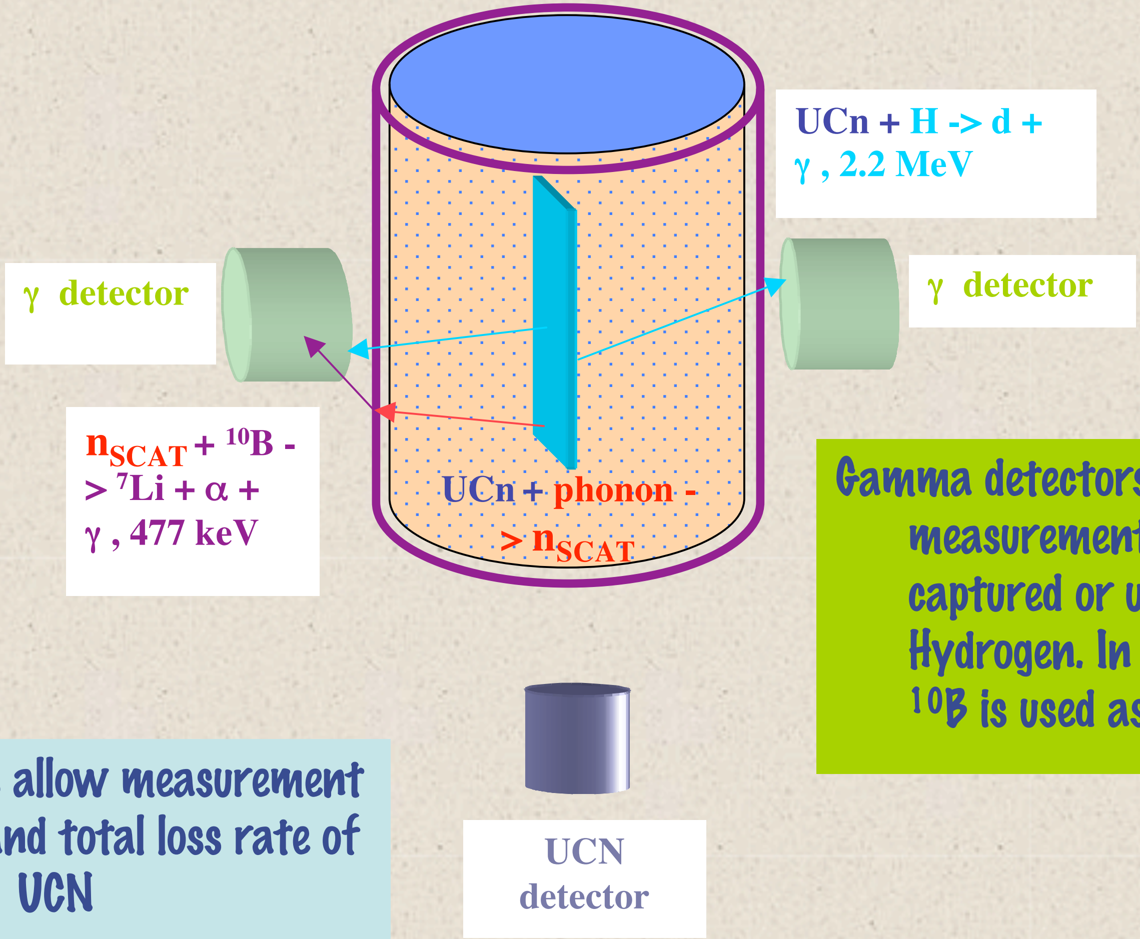
* SSD is the NIST Standard Reference Database no. 42 by P. R. Watson, M. A. Van Hove, and K. Hermann. The pictures have been prepared from NIST SSD output and processed with BALSAC by K. Hermann.

Picture from the NIST Surface Structure Database (SSD)*



Geometry of Cu(100)+C2H4 disordered

Layout of Low temperature Surface study with UCN



Gamma detectors allow measurement of UCNs that are captured or upscattered by Hydrogen. In the latter case a ^{10}B is used as a converter

UCN detectors allow measurement of UCNs flux and total loss rate of UCN

Progress in study of the UCN interaction with surface

- To develop any application of UCN to the condensed matter study we need
  - reliable theoretical model of UCN interaction that has been tested experimentally
  - Find practical solution of technical issues for successful UCN storage at low temperatures

Progress in theory of the UCN interaction with surface

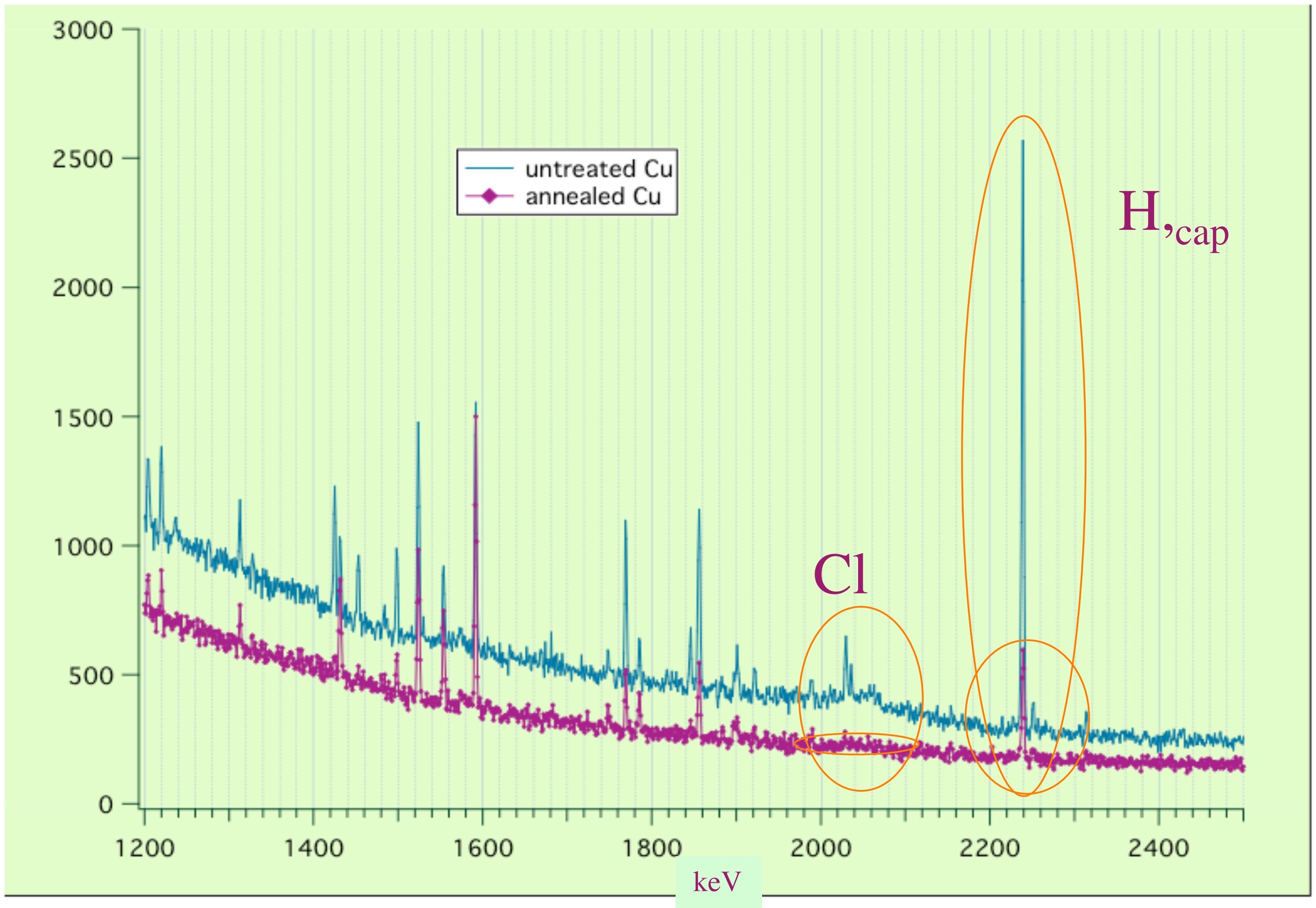
- (UCN,prompt γ) analysis has been tested and showed that UCN capture is described correctly by the optical theorem with an imaginary potential.

  Physica B 234-236(1997), JETP 115(1999), NIM A 440, 2000
- Rigorous theory of UCN coherent scattering recently was developed by S.Belyaev and A.Barabanov, Eur. Phys. J. B15(2000). It takes into account second order terms significant for multiple scattering effects. Theory verifies the use of the optical theorem for phonon scattering, whereas for liquids and amorphous materials new effects are predicted.

  (Submitted to Phys.Rev. B in 2004)
- Recent experimental study of temperature dependence of UCN losses due to incoherent inelastic scattering on Cu surface shows that on metals only a model of the surface film can explain experimental data. Model of sub-barrier losses was reliably ruled out.

  Phys.Rev. B 70 (2004)

Example of (UCN,gamma) spectrum.
H and Cl content on the surface of Cu sample



Example of calculation of the total integral probability of UCN scattering on Fomblin oil (C_3F_6O)

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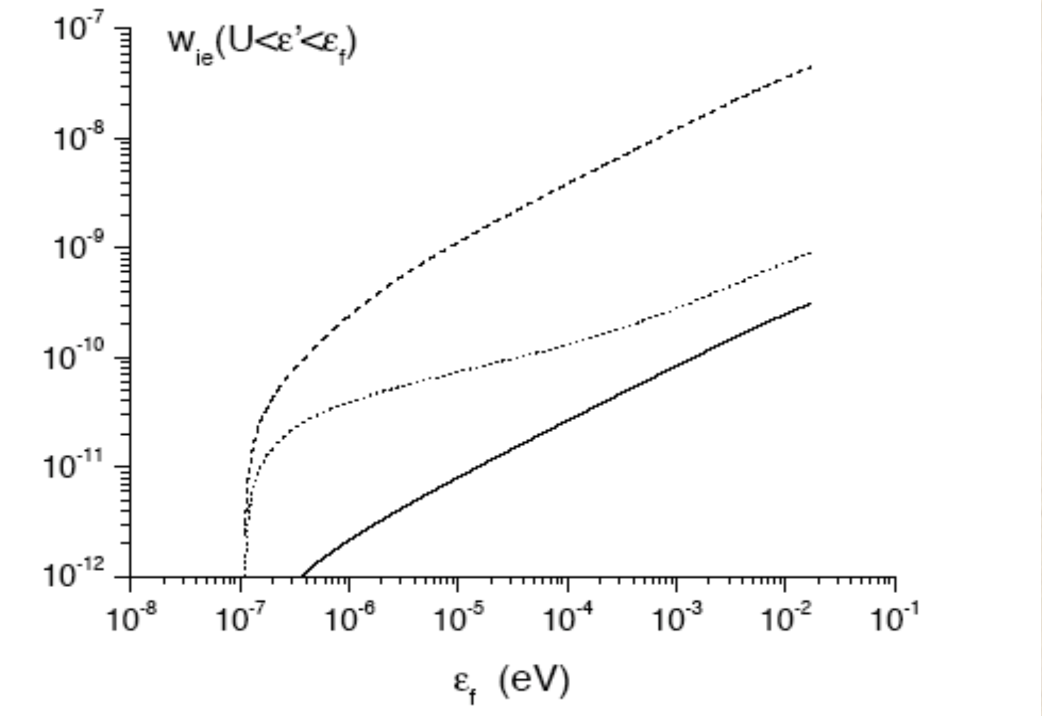
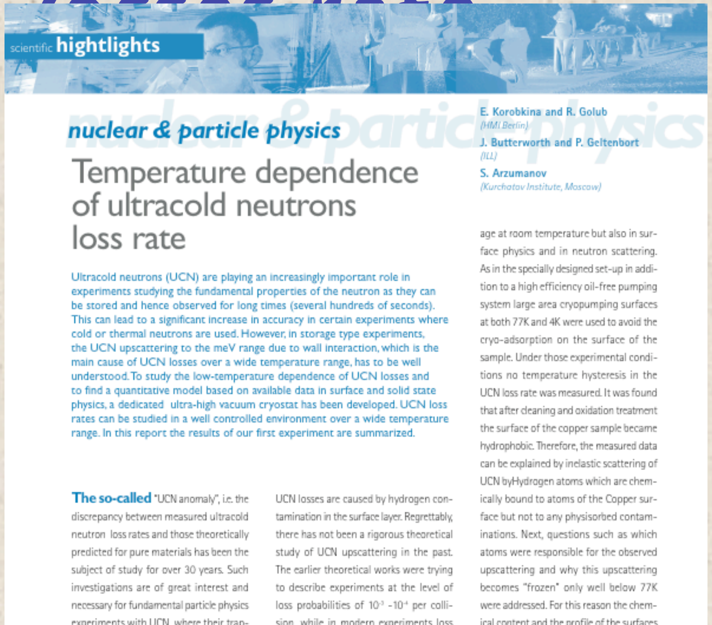


FIG. 5: Inelastic scattering for UCN of 40 neV on Fomblin oil at $T = 293$ K: the integral probability w_{ie} per bounce of transition to the interval $U < \varepsilon < \varepsilon_f$ as function of ε_f. Solid line – longitudinal sound contribution, dotted line – transverse sound contribution, dashed line – thermo-diffusion contribution.

Study of the temperature dependence of the UCN losses rate

- Low temperature behavior of the temperature dependence of UCN loss rate is crucial for different models
- We made a significant progress in study of UCN upscattering on Hydrogen in our experiment at ILL in 2001.
- Success of experiment was due to use of the sophisticated Ultra-high vacuum cryostat with the oil-free and large-area cryopumps



scientific hightlights

nuclear & particle physics

Temperature dependence of ultracold neutrons loss rate

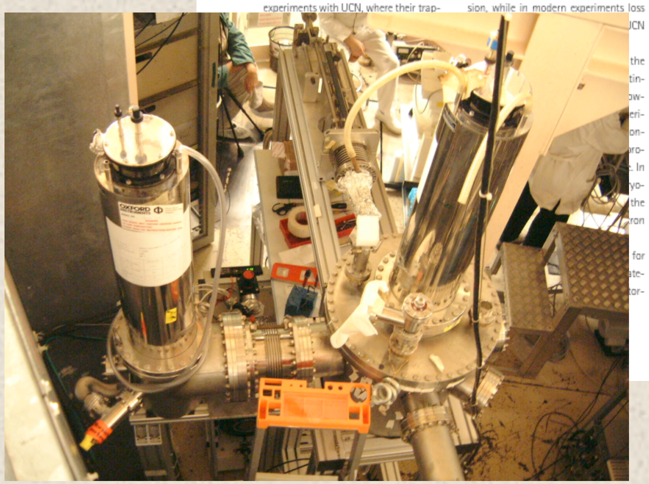
E. Korobkina and R. Golub
(HMI Berlin)
J. Butterworth and P. Geltenbort
(ILL)
S. Arzumanov
(Kurchatov Institute, Moscow)

Ultracold neutrons (UCN) are playing an increasingly important role in experiments studying the fundamental properties of the neutron as they can be stored and hence observed for long times (several hundreds of seconds). This can lead to a significant increase in accuracy in certain experiments where cold or thermal neutrons are used. However, in storage type experiments, the UCN upscattering to the meV range due to wall interaction, which is the main cause of UCN losses over a wide temperature range, has to be well understood. To study the low-temperature dependence of UCN losses and to find a quantitative model based on available data in surface and solid state physics, a dedicated ultra-high vacuum cryostat has been developed. UCN loss rates can be studied in a well controlled environment over a wide temperature range. In this report the results of our first experiment are summarized.

The so-called "UCN anomaly", i.e. the discrepancy between measured ultracold neutron loss rates and those theoretically predicted for pure materials has been the subject of study for over 30 years. Such investigations are of great interest and necessary for fundamental particle physics experiments with UCN, where their trap-

UCN losses are caused by hydrogen contamination in the surface layer. Regrettably, there has not been a rigorous theoretical study of UCN upscattering in the past. The earlier theoretical works were trying to describe experiments at the level of loss probabilities of 10^{-3} -10^{-4} per collision, while in modern experiments loss

age at room temperature but also in surface physics and in neutron scattering. As in the specially designed set-up in addition to a high efficiency oil-free pumping system large area cryopumping surfaces at both 77K and 4K were used to avoid the cryo-adsorption on the surface of the sample. Under those experimental conditions no temperature hysteresis in the UCN loss rate was measured. It was found that after cleaning and oxidation treatment the surface of the copper sample became hydrophobic. Therefore, the measured data can be explained by inelastic scattering of UCN byHydrogen atoms which are chemically bound to atoms of the Copper surface but not to any physisorbed contaminations. Next, questions such as which atoms were responsible for the observed upscattering and why this upscattering becomes "frozen" only well below 77K were addressed. For this reason the chemical content and the profile of the surfaces of the Copper samples were studied using elastic recoil detection analysis at the Ion Beam Laboratory of the Hahn-Meitner-Institute, Berlin, after the UCN measurements done at the ILL. It turned out that the Hydrogen content in the bulk of Copper (deeper than 2 µm from surface) was 0.1% compared to 8% in the surface layer ($7.2\ 10^{17}$ at/cm^2, 100Å) ; the rest was Cu (55%), C(10%), and O(25%). For such a quantity of Hydrogen two different models of the Hydrogen distribution in the surface layer can be considered. One is a homogeneous dilute solution, while the second is a hydrogenated film or clusters. In both cases the shape of the tem-



Study of the temperature dependence of UCN losses rate in 2001

- Success of data evaluation was due to use of the data of ERDA analyze made at ISL, HMI.
- ERDA analyze provide us the atomic density of all surface compounds of UCN storage bottle including Hydrogen that was of great importance!
- Analyzing our data with the data of ERDA, neutron scattering and prompt (UCN,gamma) analyze we showed, that only model of the thin water-containing film can explain experimental data. Another model (sub-barrier penetration into the bulk) was reliably ruled out, closing room for the speculation about “anomaly” in UCN interaction with the bulk.
- Published in Phys. Rev. B 70 (2004) 035409

perature dependence arises from the temperature behaviour of the inelastic upscattering cross section, while the actual loss rate depends also on the ratio between the Fermi potential of the layer, V_f and the neutron energy, E_{UCN}. For the homogeneous dilute solution $V_f > E_{UCN}$ holds. The neutrons are then totally reflected and their losses are due to the quantum effect of subbarrier (neutron energy is below the potential barrier produced by the bulk material) penetration. For the hydrogenated film or clusters one has $V_f < E_{UCN}$ because of the negative neutron scattering length of Hydrogen atoms which are more localised in this model. The losses can then be calculated using the upscattering cross section which follows the 1/v law. For the same Hydrogen concentration the two models differ significantly in the predicted loss rate and its dependence on the neutron energy. These calculations are in good agreement with prompt (n,γ) studies of UCN [2]. This experiment yielded an

model of subbarrier interaction where the loss rate is negligible. In turn, the analysis of the low temperature shape of the temperature dependence of the loss rate and its comparison with (n,γ) data at 300 K have led to the conclusion that the UCN are not being scattered by a H-Cu compound. The only way to explain the experimental data is to assume that Hydrogen is bound to a light mass in a molecule with a strong low energy vibration peak with E ≤ 8 meV. Oscillation frequencies below 10 meV are rather unusual for metal hydrides but typical for intermolecular vibrations of molecules weakly bound to a crystal. A literature search of phonon spectra for different Hydrogen compounds revealed that ordinary ice has a remarkably strong translational branch with a low energy peak at 7 meV. Such a molecule is light, has a negative Fermi potential, is commonly present on surfaces and tends to adsorb preferably in the form of clusters. Calculations of the UCN upscat-

Thus, the presence of ice clusters embedded into the surface oxide layer could explain reasonably well both the shape of the temperature dependence and the absolute value of the loss rate. A similar behaviour was observed for UCN absorption in stainless steel samples where about 1% of Titanium gave rise to the same loss rate as 50% of Iron due to the presence of Ti-C clusters on the surface with $V_f < E_{UCN}$ [2]. At present, the subbarrier model of UCN upscattering is only consistent with the experimentally determined loss rate for vapour deposited heavy water ice [3]. For metals, however, the film or cluster model describes much better the experimental results.
Finally, at low temperatures the loss rate is also extremely sensitive to the lowest frequencies of Hydrogen oscillations, which are common, for instance, in ice and glassy states of amorphous materials. Therefore, the upscattering of neutrons will dominate the losses even below liquid nitrogen tem-
... being so trouble-
for so many years,
...llenging opportu-
...y ultra-low energy
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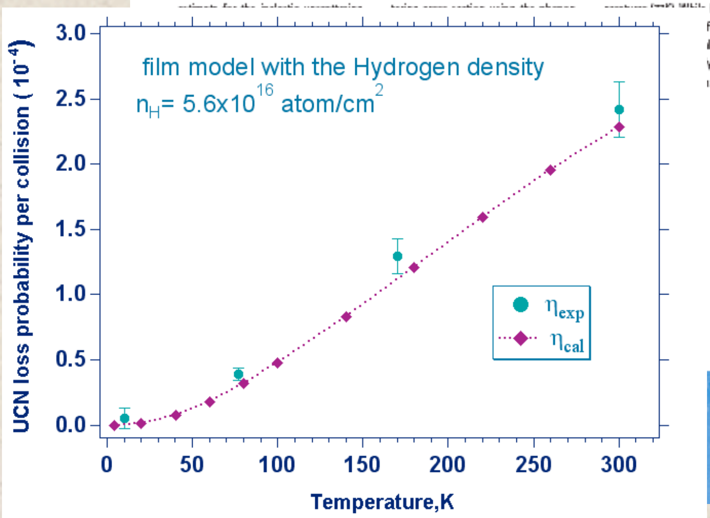

Progress in experimental UCN storage

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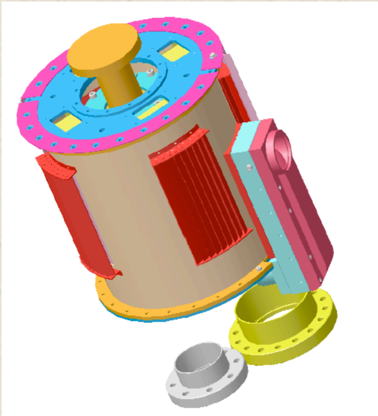
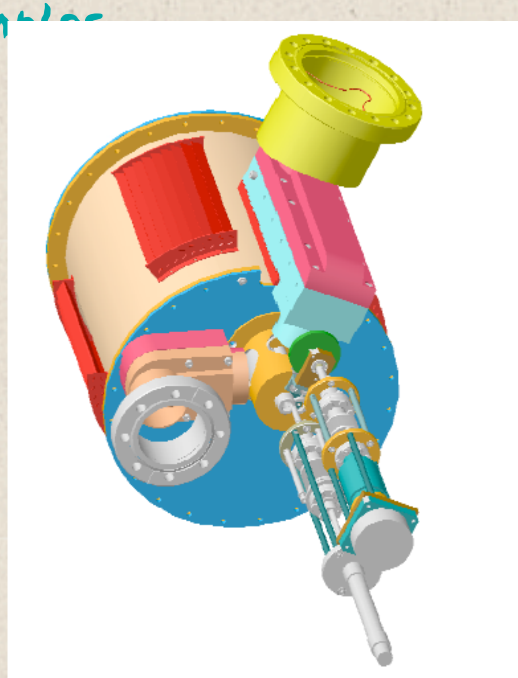
- Since we revealed that the chemically bound water is a main cause of the low temperature upscattering, we began to search for a procedure of the surface treatment that eliminate UCN upscattering on the walls at temperatures below 77K.
- We also re-designed and re-build our cryostat to improve count rate and developing new kind of UCN shutter
- In summer 2004 we tested out new set-up.

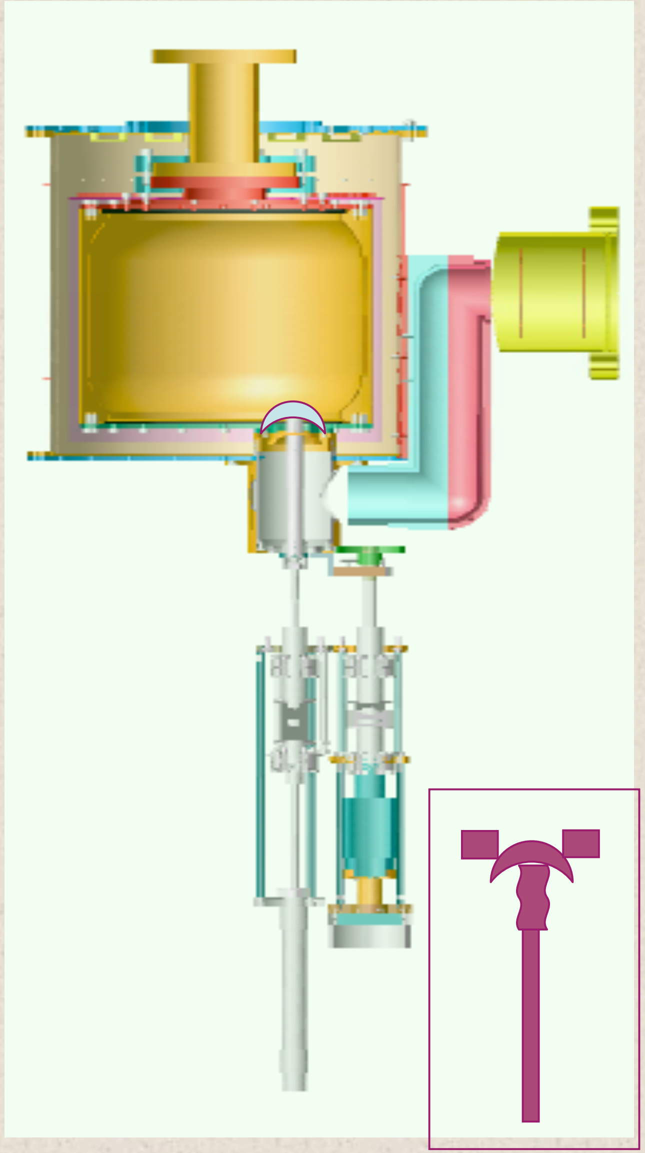
New modification of UHV cryostat



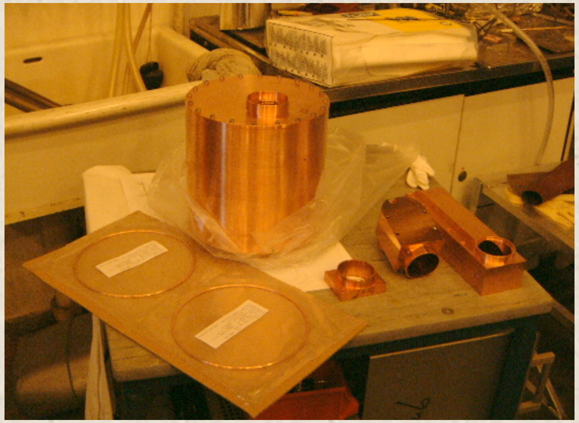
- Improvement of the storage time
- Detection efficiency
- Study of samples



- Improvement of pumping
- decreasing of LN and LHe consumption
- Low temperature UCN valve

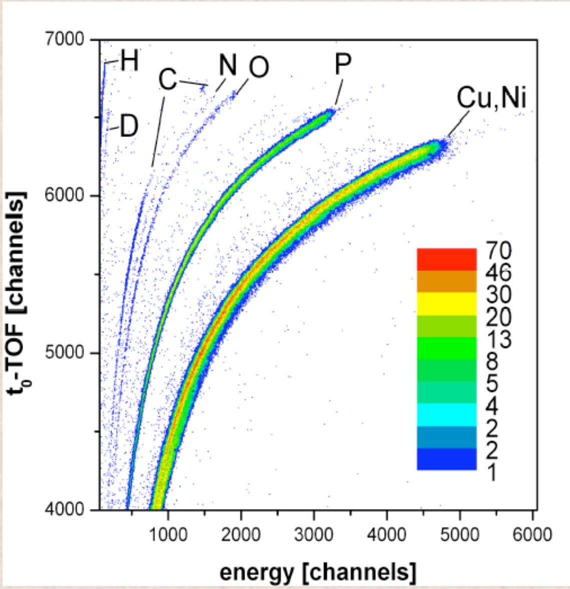


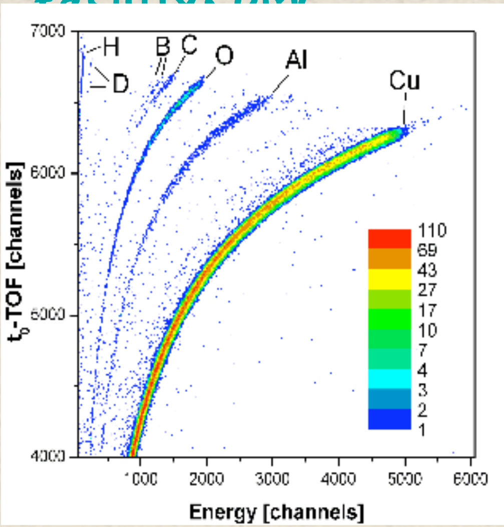
UCN storage bottle



Improvement of the storage time:

- Pure metal, no welding
- •Helicoflex Cu sealing
- •Surface treatment controlled by ERDA analysis on ISL facility, HMI





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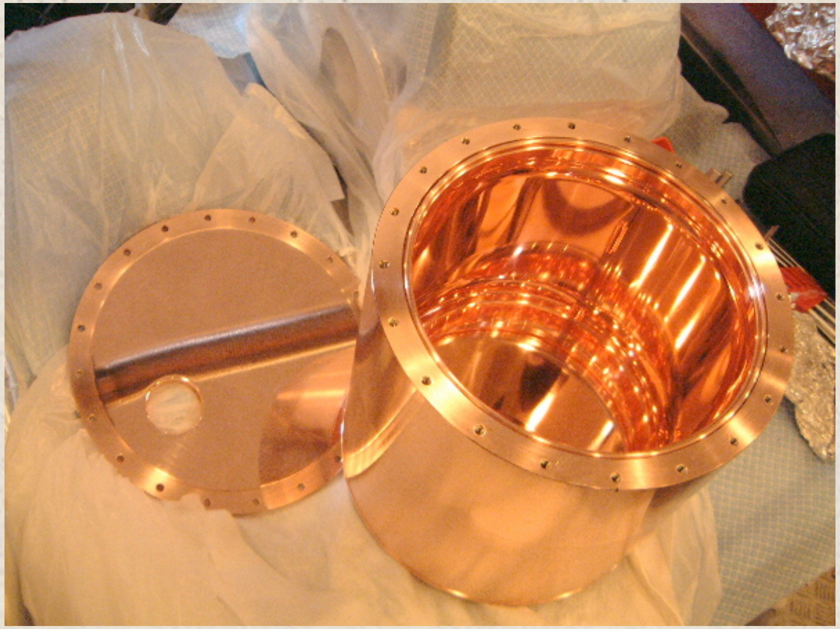
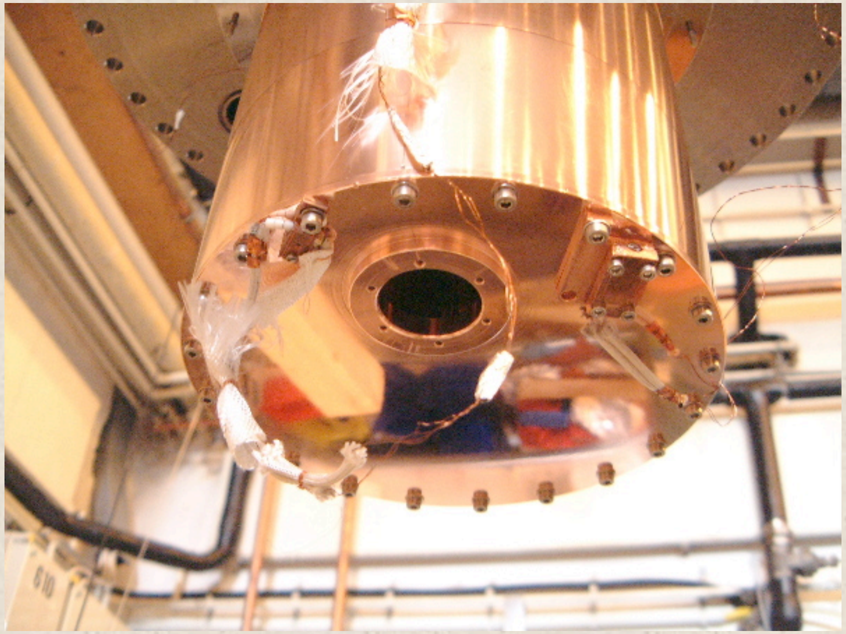
ILL test, July 2004

The UCN bottle was mounted in Berlin, then assembled cryostat was shipped to Grenoble.

- Right – view of the polished surface of the bottle inside

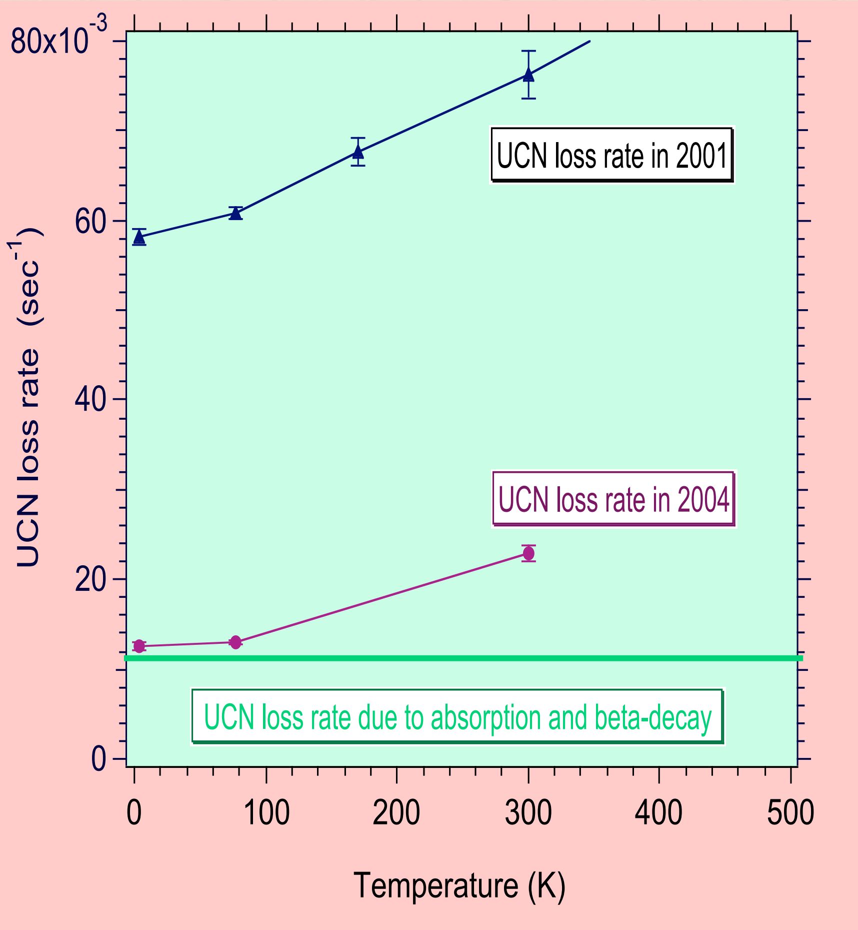




- Bottom – view of the UCN bottle and UCN shutter opening outside

The inside surface was treated the same way as small samples

Temperature dependence of UCN losses, ILL run 2004, preliminary data



- The new experimental data shows that our treatment indeed removed the low temperature UCN upscattering below 77K !
- This means we indeed have no water contamination and no vacuum contaminations
- The new construction of the bottle and UCN shutter allowed us approach very close the theoretical limit of the storage time, i.e. loss rate due to the beta-decay and absorption by Copper nuclei.

Technical development
Summary

- We found the surface treatment procedure that protect metals from contamination on atmosphere and can be easy evaporated in vacuum
- Copper is a metal that is difficult to protect. Our test shows that Stainless steel and Ni have even less contaminations with the same cleaning.
- Our low temperature shutter worked very good, the loss probability was $5x10^{-5}$. This can be improved in future.
- we are ready now start test with samples and (n,gamma) technique

UCN elastic scattering - Anderson localization

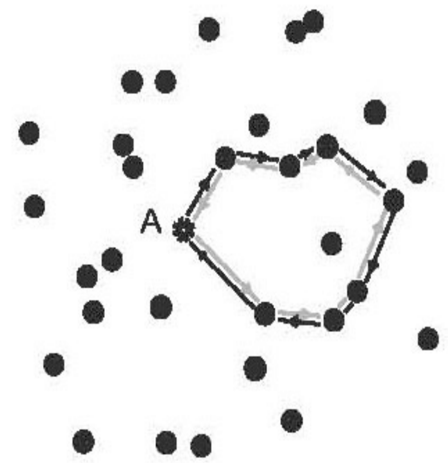


FIG. 1. Anderson localization of waves in disordered systems originates from interference in multiple elastic scattering.

- Theoretically it was proposed for electrons, photons, microwaves,for instance, P.W.Anderson Philos.Mag.B52(1985)505.
- But the experimental observation still has no success due to strong interaction with the media (absorption)

Anderson localization with UCN

- Measurement with UCN was proposed by Dr. B. Meshcherov, Kurchatov Institute, Phys.Solid State38 (1996)598
- At present there was 3 attempts to measure Anderson localization at ILL one - group of Prof. D. Dubbers, two - group of Dr.B.Meshcherov
- Experimental set-up is quite simple, while it turned out impossible to make a sample of the fine nanoparticles without their clusterisation.
- the nanoparticles should have high potential and small absorption - diamond seems the only candidate where conditions of the localisation can be approached quite close.
- Nanoparticles in the liquid helium can be a suitable sample, because of the very small losses

Summary

- UCN inelastic scattering
  - Surface study with (UCN, gamma) analysis at low temperatures

  we found solution how to decrease the background from the storage bottle itself

  we are ready now start test with samples and (n,gamma) technique
  - Theory of UCN interaction with the bulk and films

  The rigorous theory of the coherent inelastic scattering has been developed. The model for the non-phonon incoherent scattering on Hydrogen still has to be developed
- UCN elastic scattering - Anderson localization
  - Technical issues of the sample preparation still are a challenge