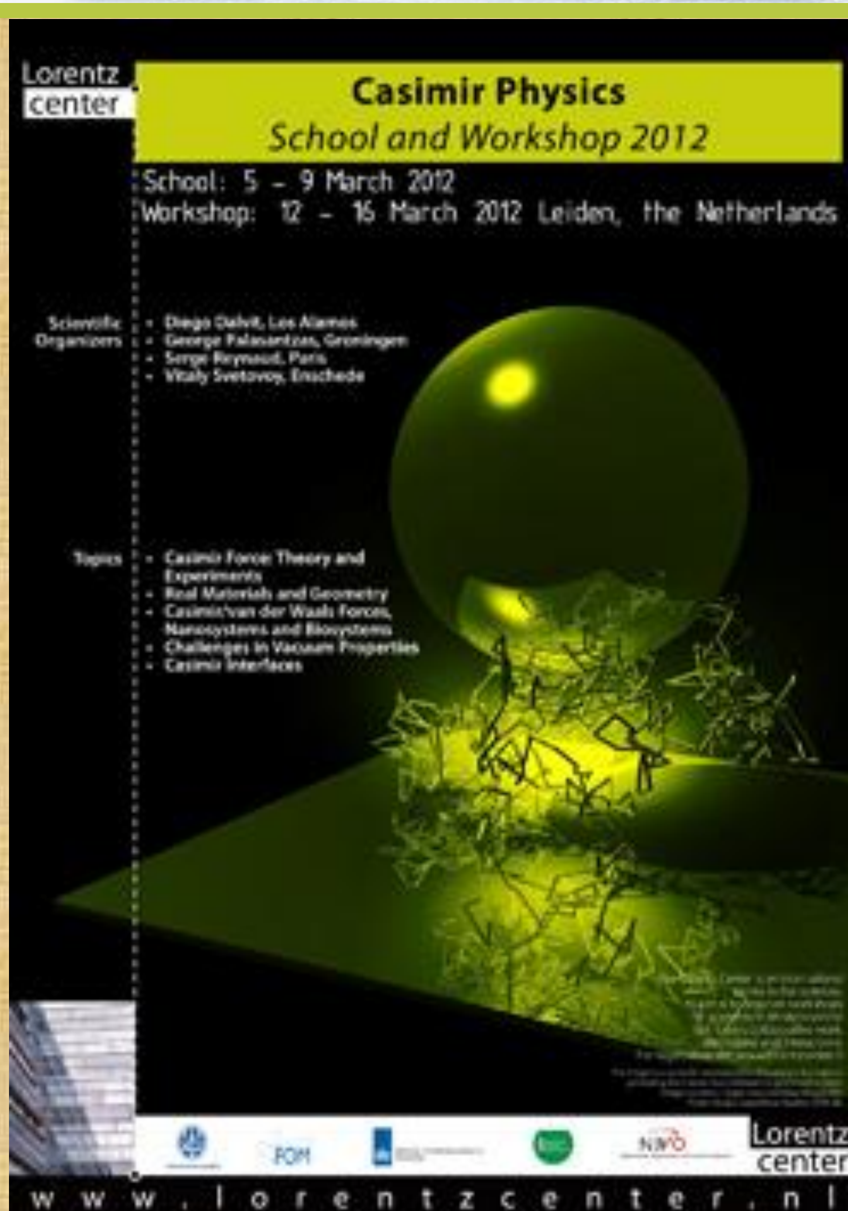
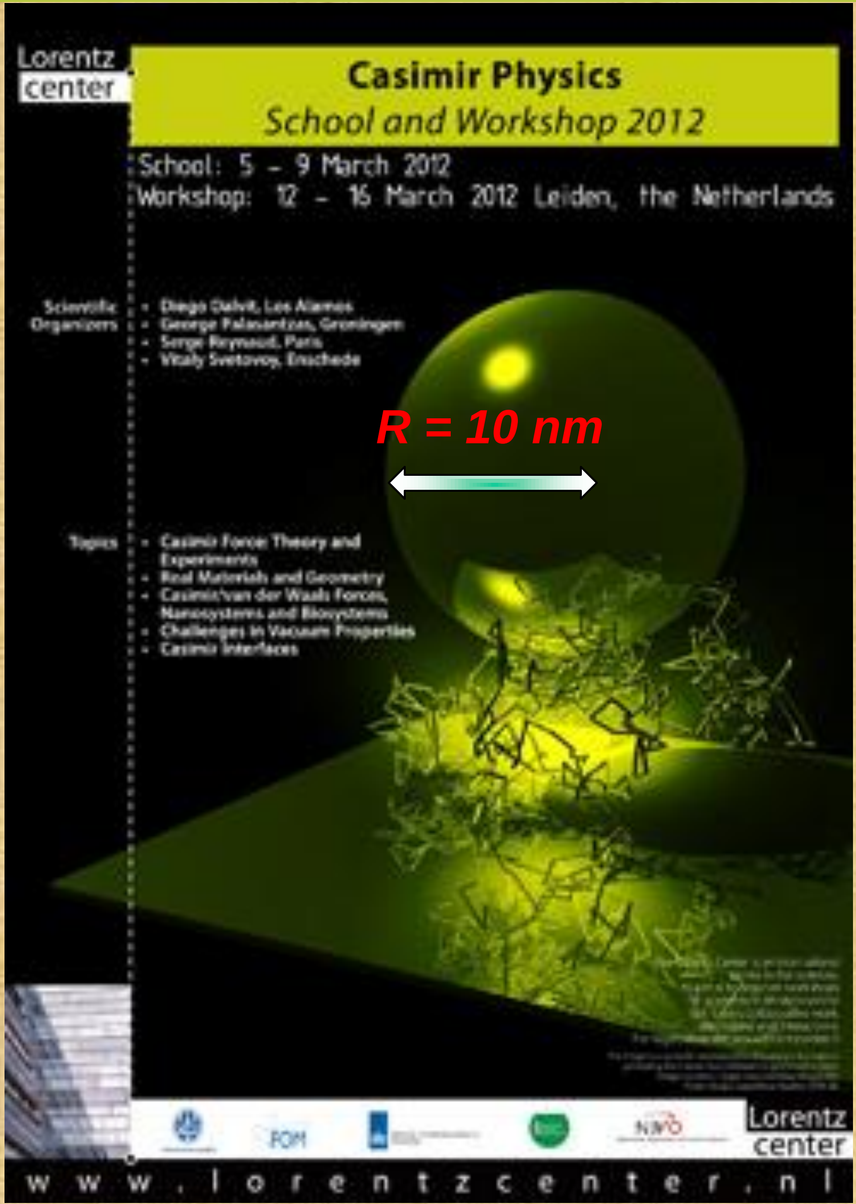
Quantum levitation of nanoparticles



Quantum levitation of nanoparticles



Quantum levitation of nanoparticles

1. Physical adsorption of nanoparticles; properties of van der Waals/ Casimir-Polder potential wells; properties of nanoparticles trapped in the wells
2. « Small heating » of ultracold neutrons (UCNs) in collisions with such levitating nanoparticles: Theory versus Experiment
3. Applications: studies of surface potentials; surface physics, chemistry, biology; systematics in neutron-lifetime and other precision experiments with UCNs

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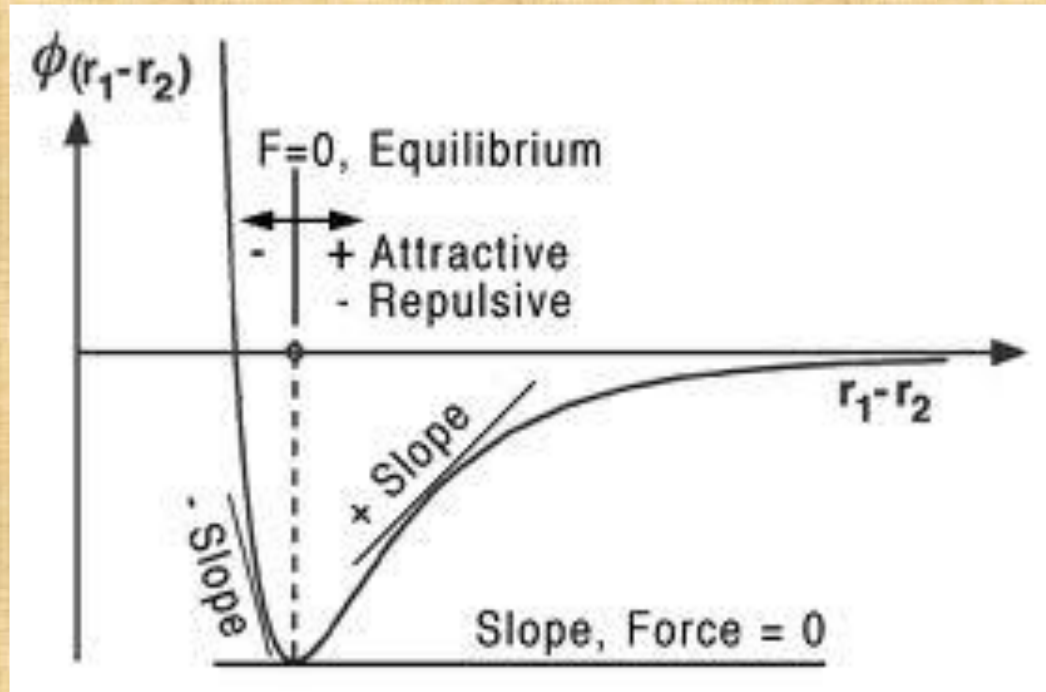
Physical adsorption

Surface diffusion of atoms, molecules and clusters, physically adsorped in the potential well associated with van der Waals/ Casimir-Polder potential (vdW/CP), plays a key role in various phenomena in physics, chemistry, biology, in applications.



The interaction is affected at the nanometer scale by « close to contact » effects depending on roughness and surface state

This quantum dispersion force, originating from vacuum fluctuations, is attractive above the molecular scale and is usually repulsive at the molecular scale so that the potential well exhibits a minimum at the nanometer distance

Physical adsorption of nanoparticles

The shape of the vdW/CP potential well could be calculated from a general expression involving only scattering properties of the surface and the nanoparticle [Maia Neto, P.A., Lambrecht, A., and Reynaud, S. *New J. Phys.* 2006, Vol. 8, 243].

For instance, in the case of diamond nanoparticles above copper surface,

at long distances [A. Canaguier-Durand et al., *Phys. Rev. A.* 83 (2011) 032508]:

$$V_{CP}(L) = -\frac{4\pi C_4 R^3}{3L^2(L+2R)^2} \quad C_4 = \frac{9\hbar c\,\alpha_0}{32\pi^2} \quad \alpha_0 = \frac{n_0^2-1}{n_0^2+2}$$

at short distances:

$$V_{vdW}(L) = -\pi C_3\left(\frac{2R(L+R)}{L(L+2R)} - Log\left(\frac{L+2R}{L}\right)\right) \quad C_3 = \frac{3\hbar c\,\alpha_0}{16\left(\sqrt{2}\lambda_P + \sqrt{1-\alpha_0}\,\lambda_1\right)}$$

Thus we get two limiting cases: van der Waals (near-field) and Casimir (far-field) interactions:

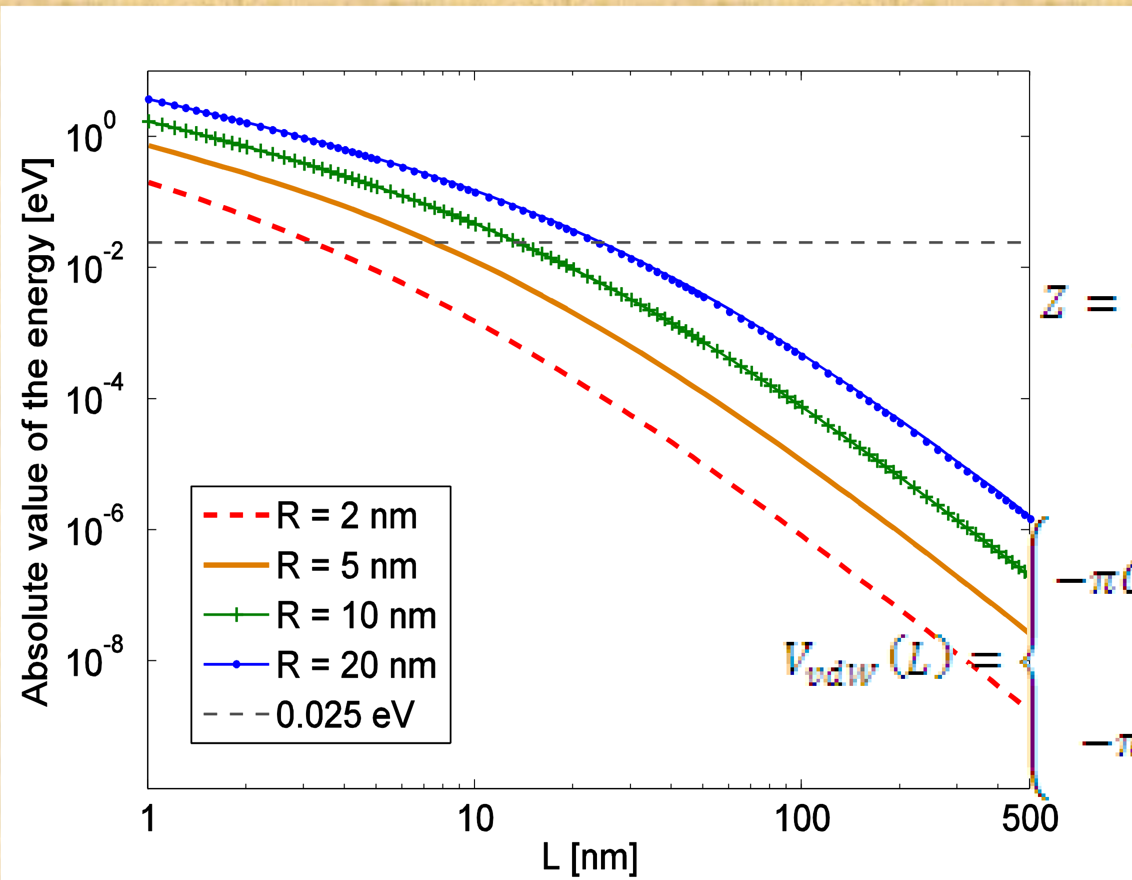
As long as the nanoparticle size is significantly smaller than so-called plasma wavelength (all practically interesting cases), the interaction of each atom in the nanoparticle is not significantly affected by presence of other atoms

Properties of nanoparticle quantum states

Quantum states are well established, however: very large number of quantum states

Quasi-classical behaviour due to very large number of quantum states involved

Nanoparticles spend most of time in their « turning points », far from surface: Casimir-Polder interaction is essential



distribution over quantum states:

$$N_i = \frac{N}{Z} exp\left(-\frac{E_i}{k_B T}\right)$$

$$Z = \sum_i exp\left(-\frac{E_i}{k_B T}\right) \approx \int_{E_0}^{\infty} exp\left(-\frac{E}{k_B T}\right)\frac{dn}{dE}(E)dE$$

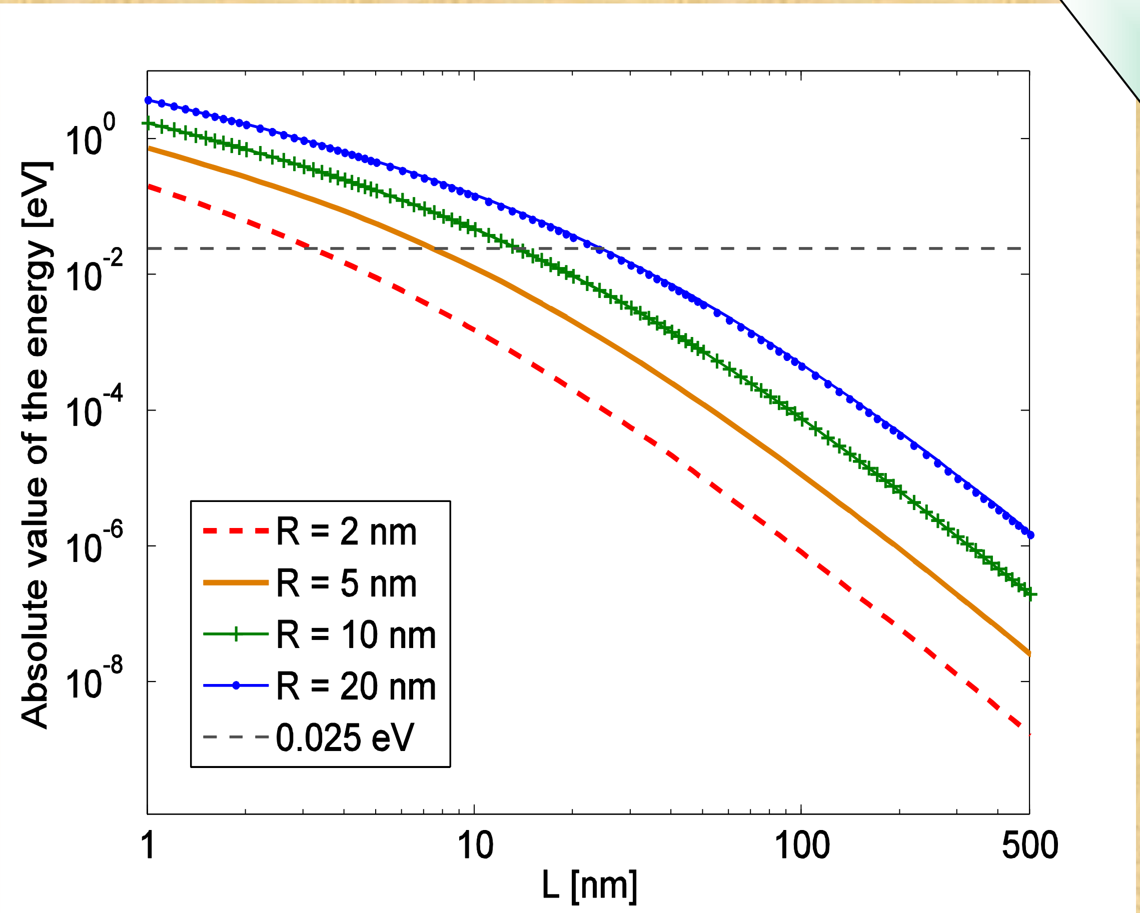
normalization at short distances:

$$V_{vdw}(L) = \begin{cases} -\pi C_3\left(\frac{2R(L+R)}{L(L+2R)} - Log\left(\frac{L+2R}{L}\right)\right), L_c < L < \lambda_p \\ -\pi C_3\left(\frac{2R(L_c+R)}{L_c(L_c+2R)} - Log\left(\frac{L_c+2R}{L_c}\right)\right), L < L_c \end{cases}$$

Physical adsorption of nanoparticles

The thermal kinetic energy is $\sim \frac{3}{2} k_B T$,

while the depth of the potential well is proportional to the nanoparticle mass (if the mass is small enough)

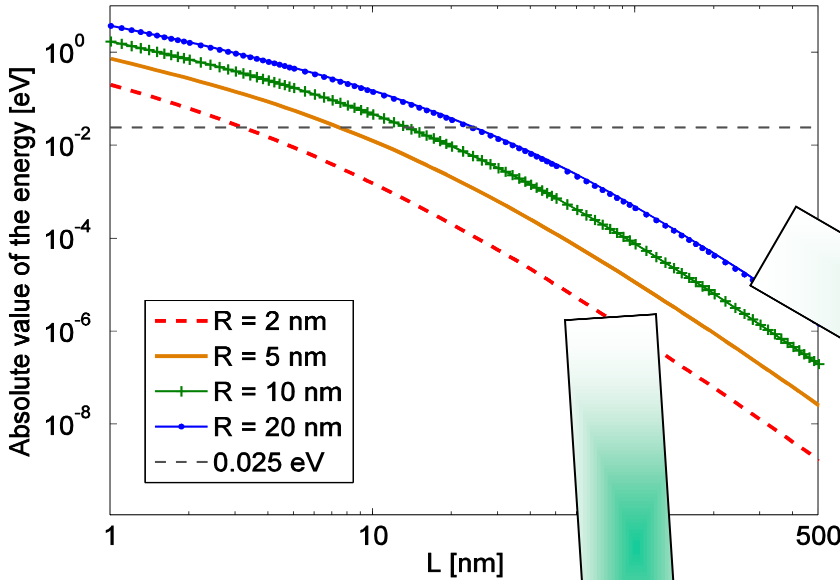


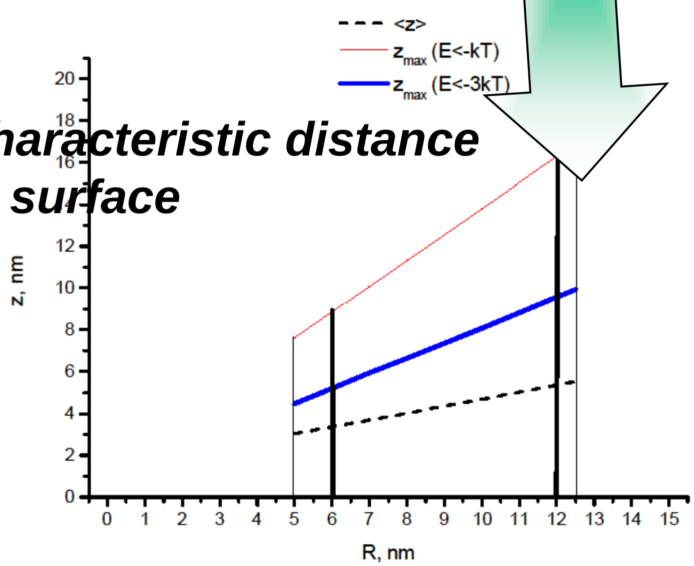
Very deep potential well in the direction perpendicular to surface;

Diffusion along surface;

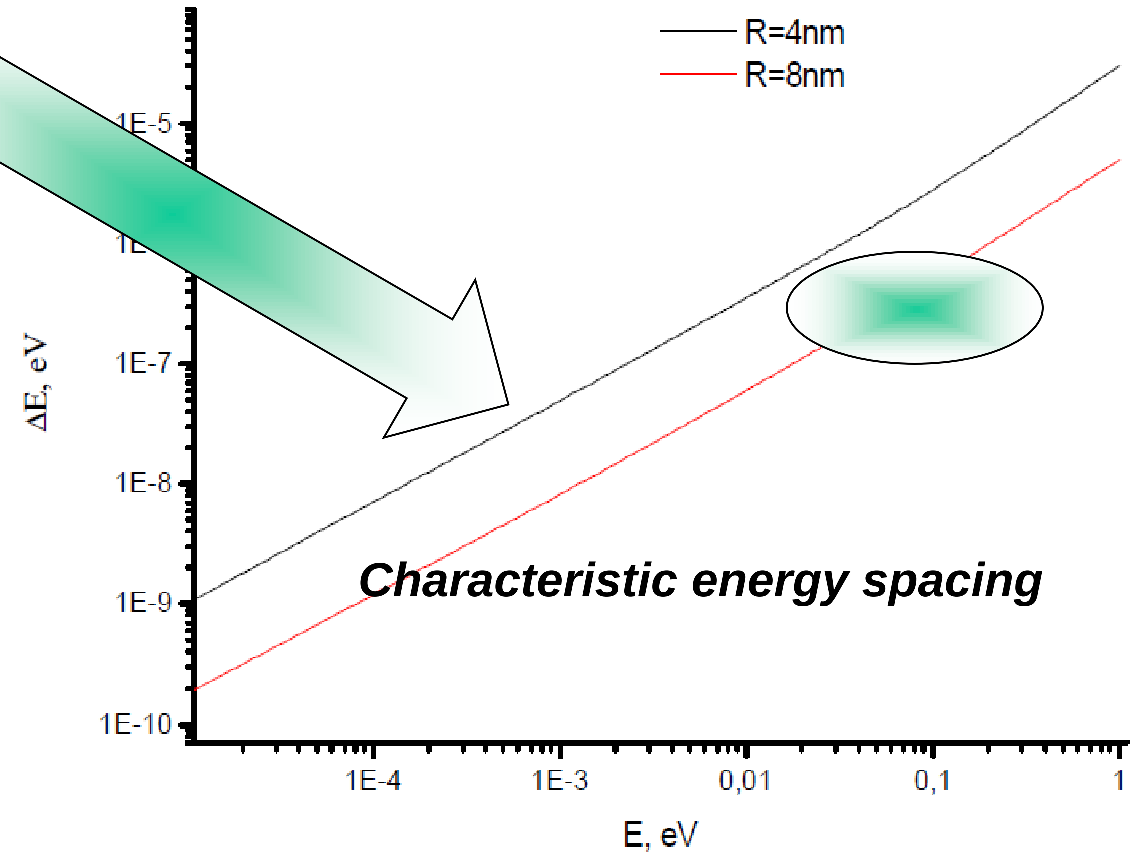
Roughness mixing velocity components

Properties of nanoparticle quantum states





Characteristic distance to surface



Characteristic energy spacing

UCN scattering on nanoparticles

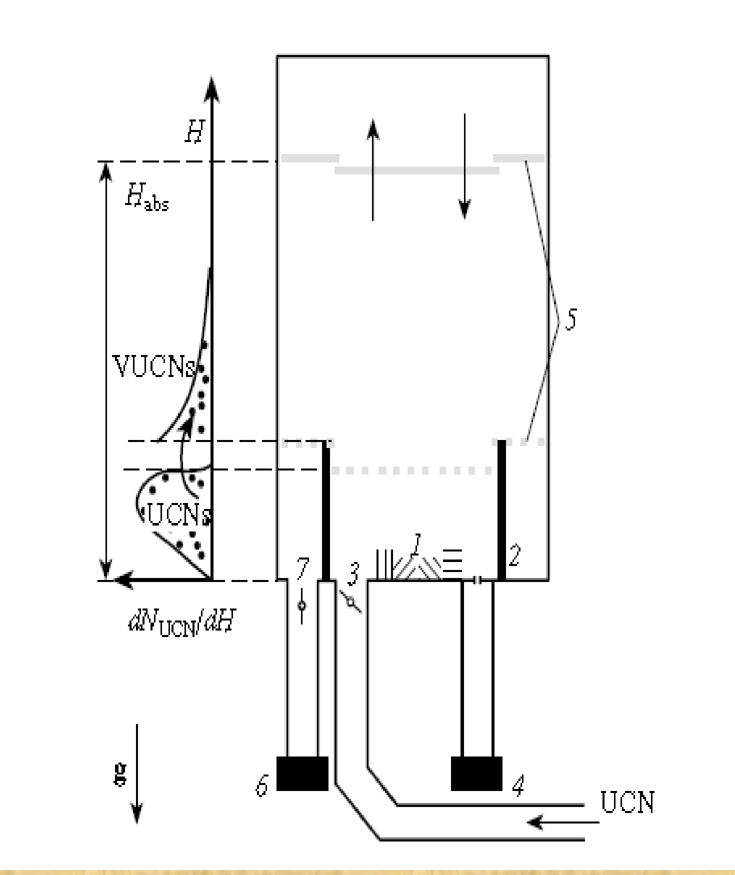
The neutron-nanoparticle interaction cross-section could be written, at certain conditions, as follows (with standard notations):

$$\frac{d\bar{\sigma}}{dE}=\frac{1}{2mk_n}\left(\frac{M}{2\pi k_B T}\right)^{\frac{3}{2}}\int_0^{\infty} exp\left(-\frac{MV^2}{2k_B T}\right)dV\int_{k_{min}}^{k_{max}} dk_0\int_0^{2\pi}\left|f_B(k_0,V,E,\varphi)\right|^2 d\varphi$$

$$\begin{cases} \left|mV-k_n\right| \le k_0 \le mV+k_n \\ \left|\sqrt{k_n^2+2mE}-mV\right| \le k_0 \le \sqrt{k_n^2+2mE}+mV \end{cases}$$

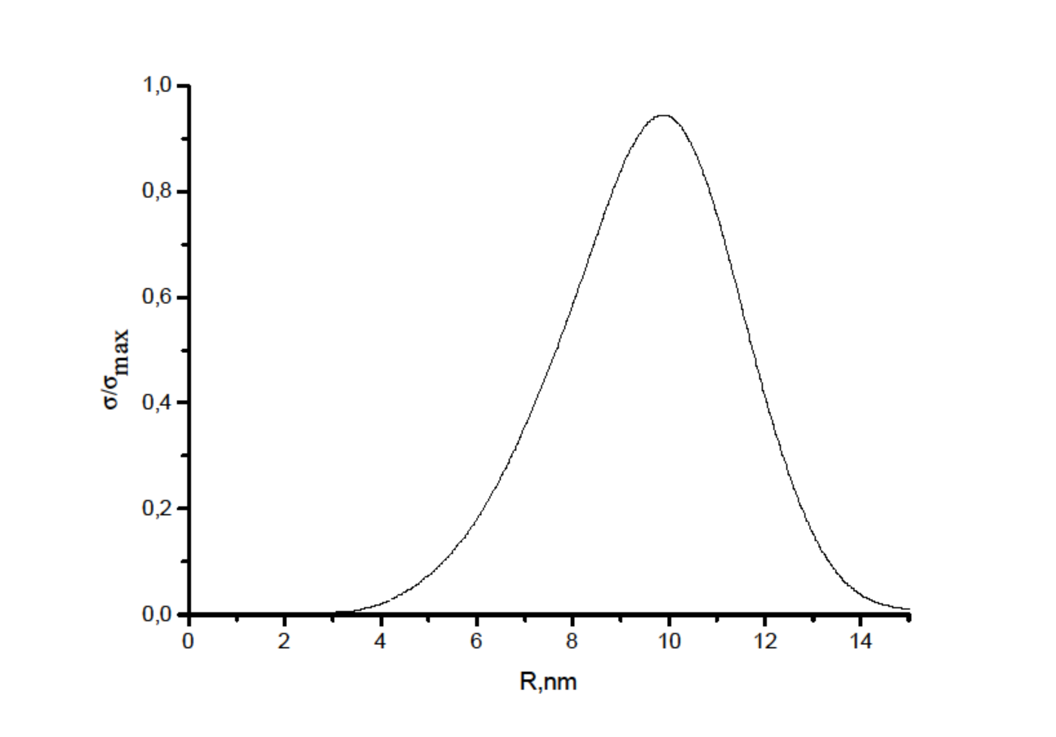
The Born amplitude:

$$f_B(q)=-\frac{2mRU_0}{q^2}\left[\frac{\hbar\sin\left(\frac{qR}{\hbar}\right)}{qR}-\cos\left(\frac{qR}{\hbar}\right)\right]$$



Resonance character of the UCN-nanoparticle interaction

Note: $d\bar{\sigma}/dE \sim R^6$ ***also large nanoparticles are slow, therefore***



Existing data for the case of diamond nanoparticles levitating above copper surface, or above « sand » of other diamond nanoparticles:

$$\bar{R}_{diamond}^{(temperature)} = 9.5 \pm 0.6\ nm$$

$$\bar{R}_{diamond}^{(average\ size)} = 8.5 \pm 0.5\ nm$$

$$\bar{R}_{diamond}^{(spectrum)} = 9.4 \pm 0.4\ nm$$

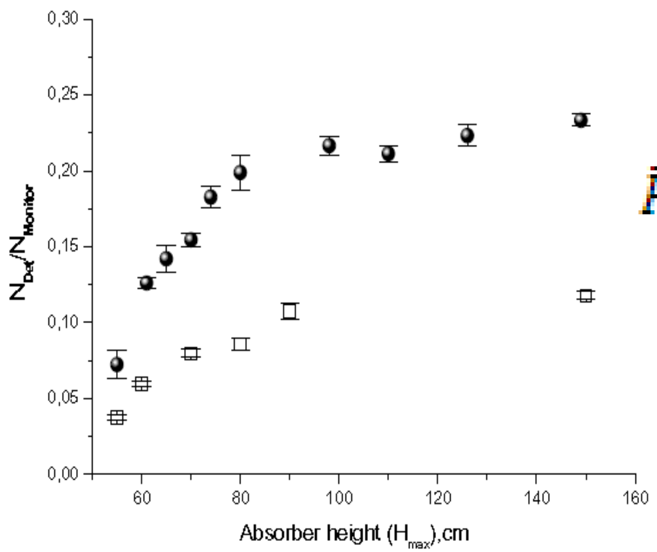
Existing data for stainless steel surafaces:

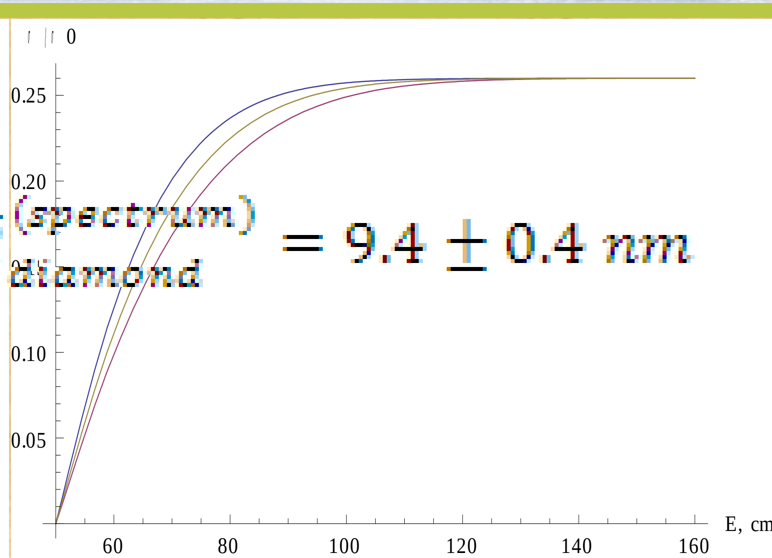
$$\bar{R}_{stainless\ steel}^{(spectrum)} = 6.3 \pm 0.3\ nm$$

$$\bar{R}_{stainless\ steel}^{(average\ size)} = 6.6 \pm 0.3\ nm$$

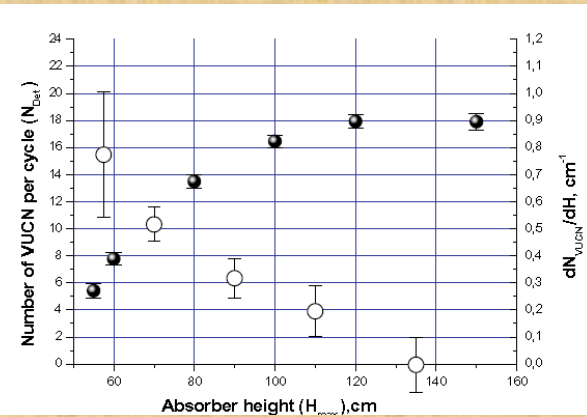
Masses are equal !

Resonance character of the UCN-nanoparticle interaction

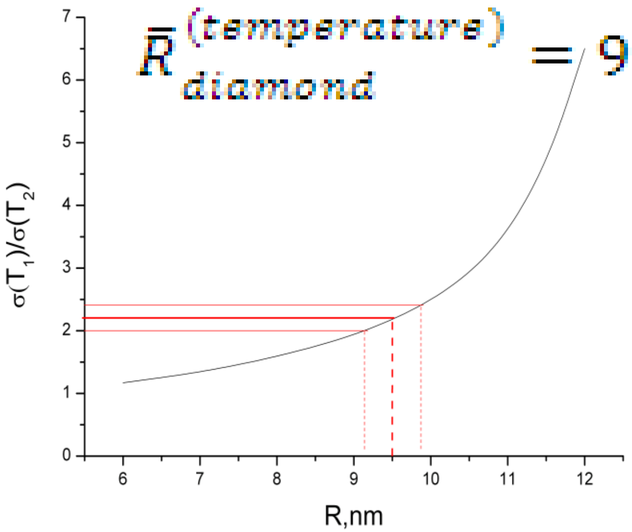




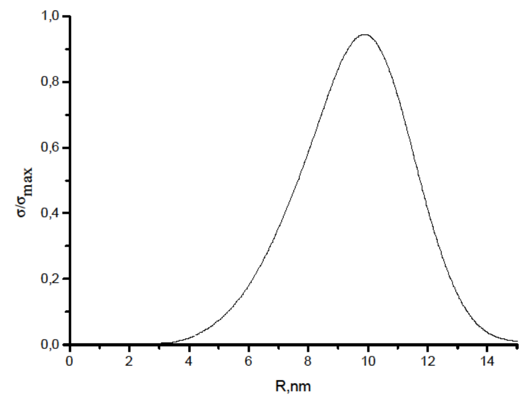
$$\bar{R}^{(spectrum)}_{diamond} = 9.4 \pm 0.4\ nm$$

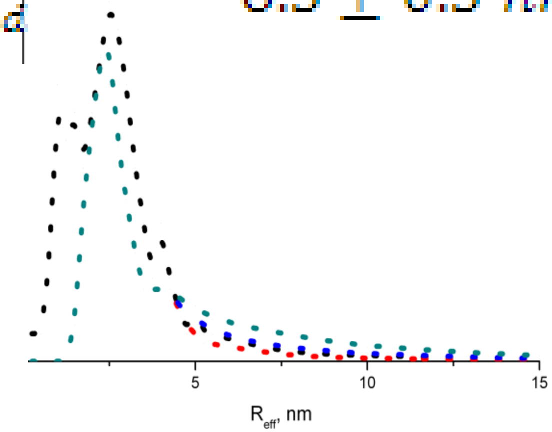


$$\bar{R}^{(temperature)}_{diamond} = 9.5 \pm 0.6\ nm$$

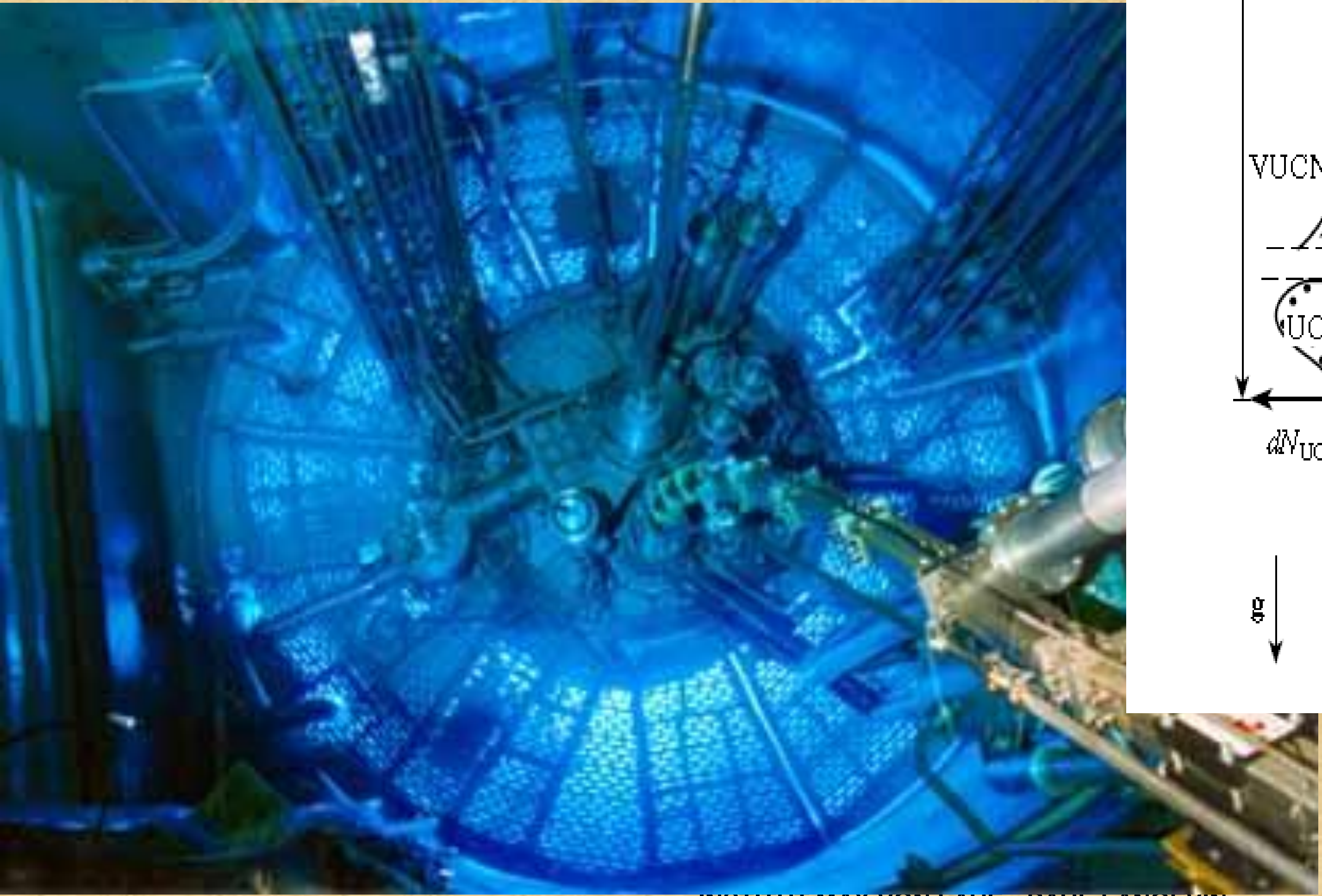


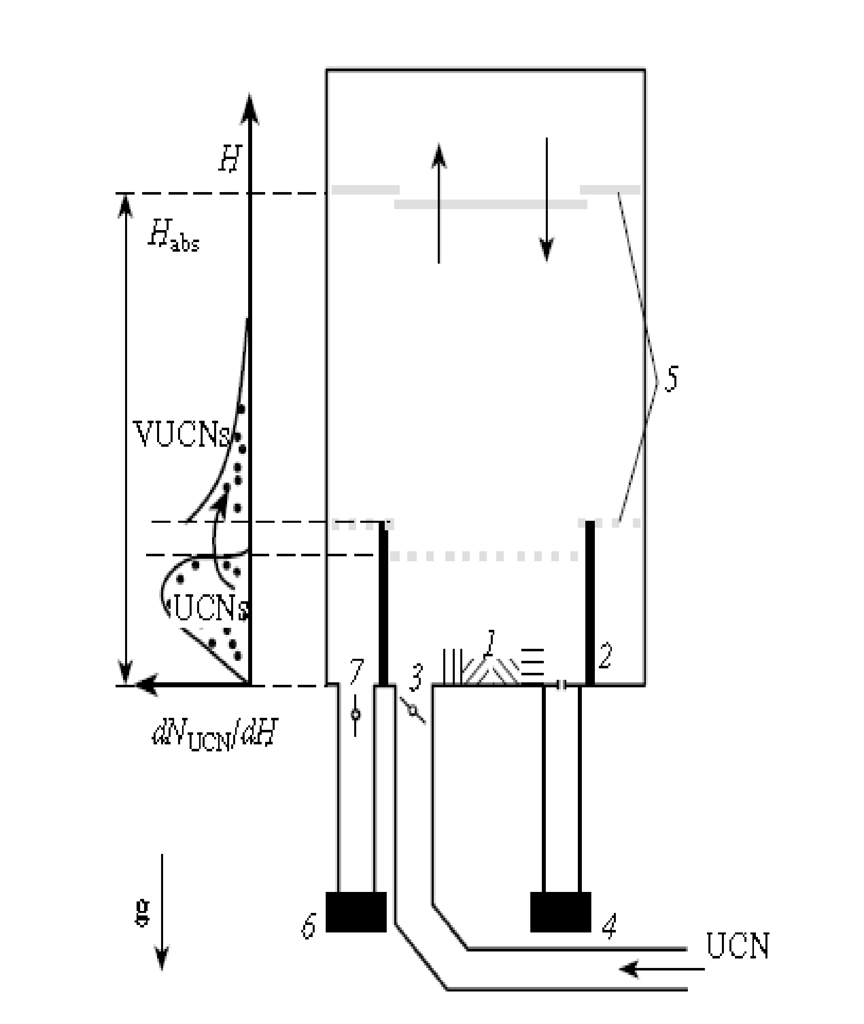
$$\bar{R}^{(average\ size)}_{diamond} = 8.5 \pm 0.5\ nm$$





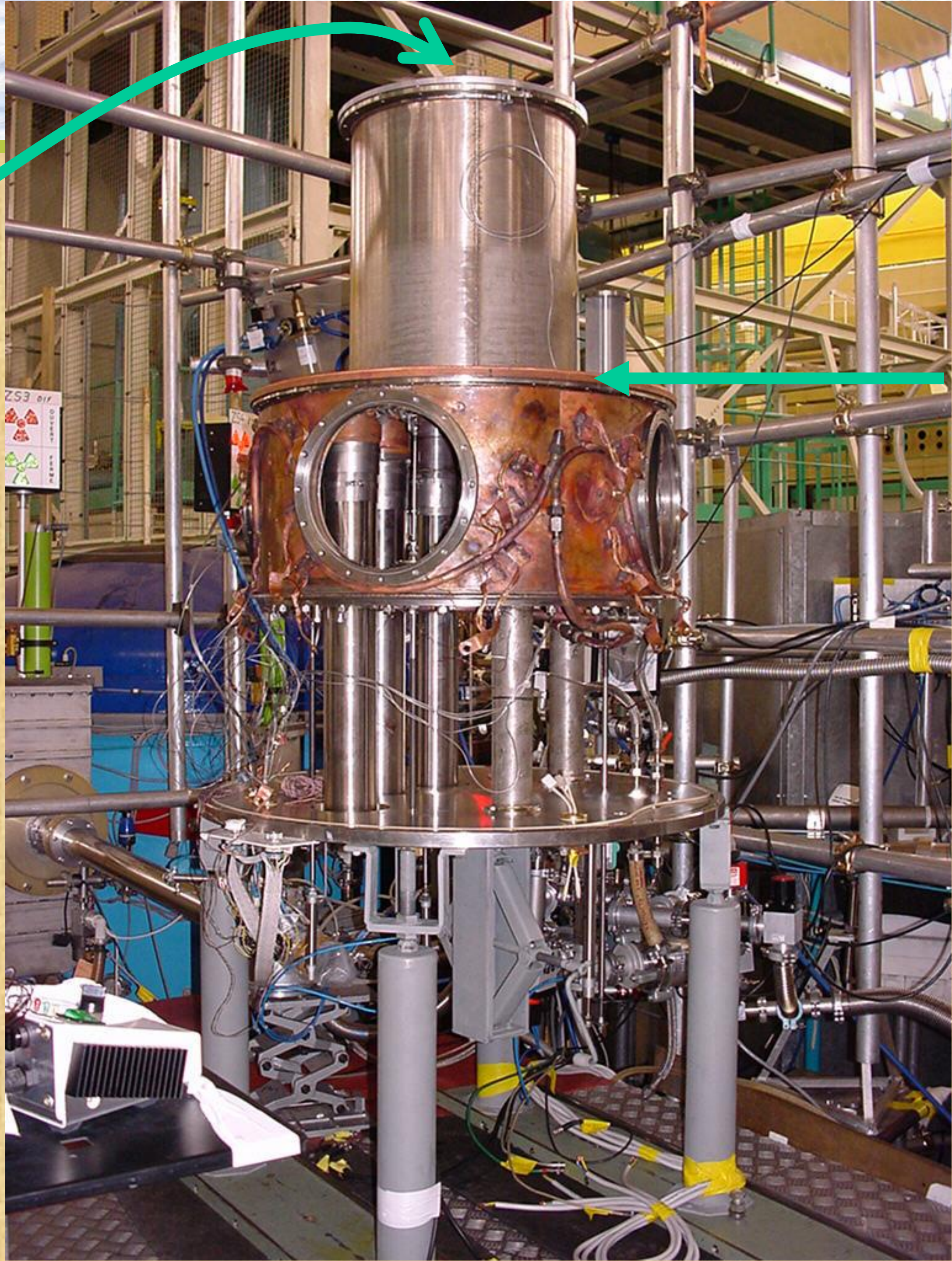
Experimental method





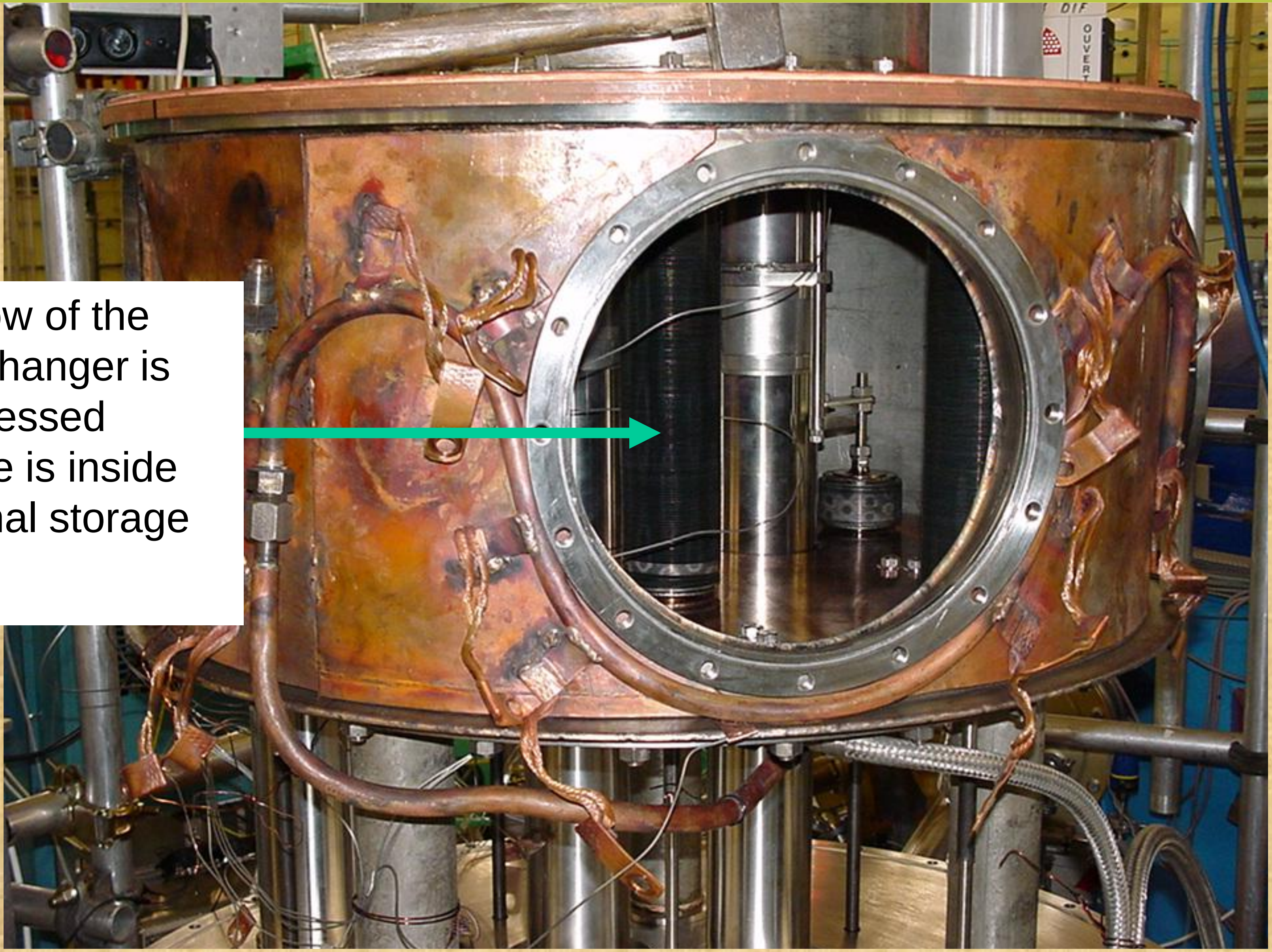
Spectromter

The internal storage volume for UCN
(copper inside)



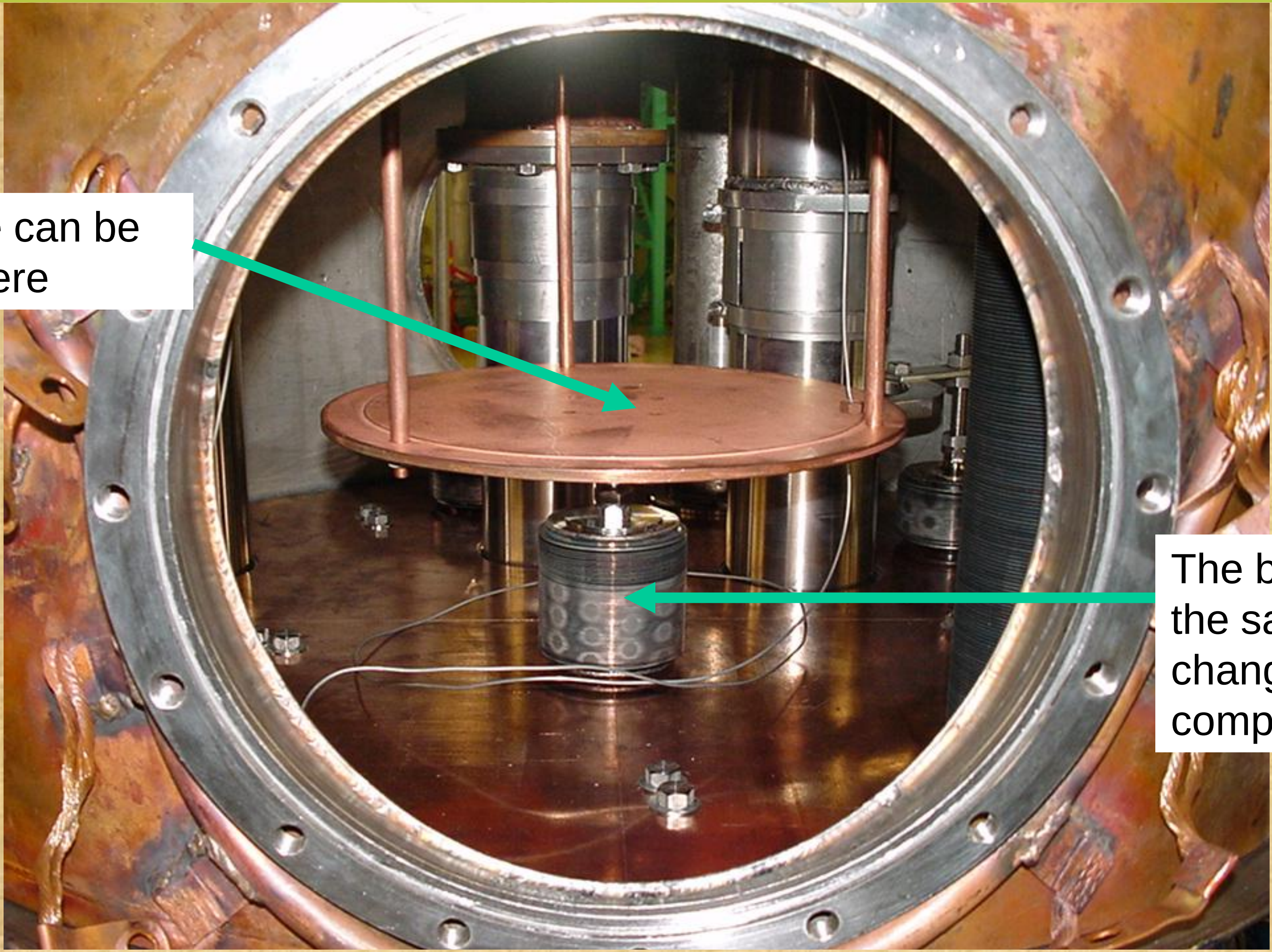
The bottom for the internal storage volume and the external storage volume

Spectrometer



The bellow of the sample changer is decompressed (a sample is inside the internal storage volume)

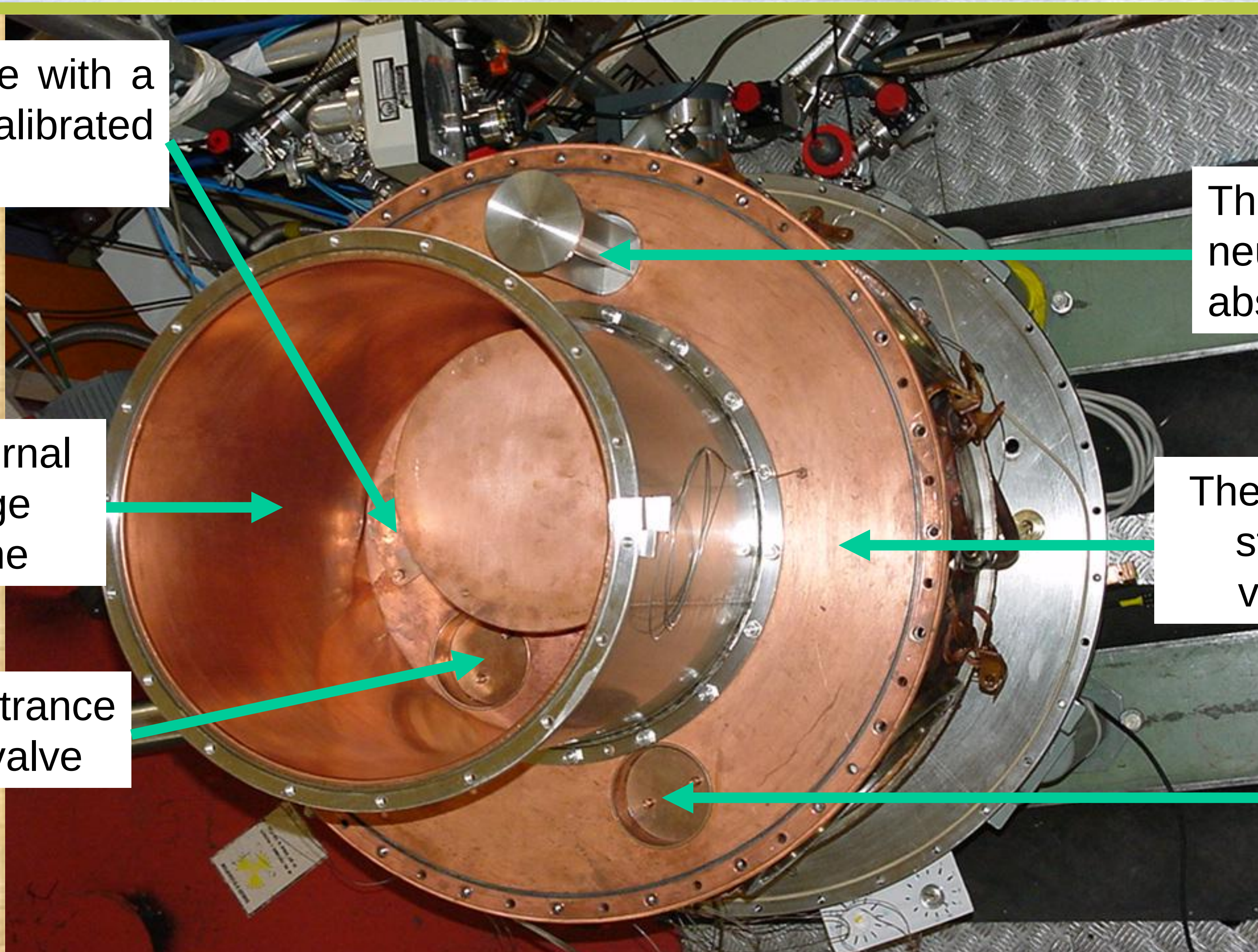
Spectrometer



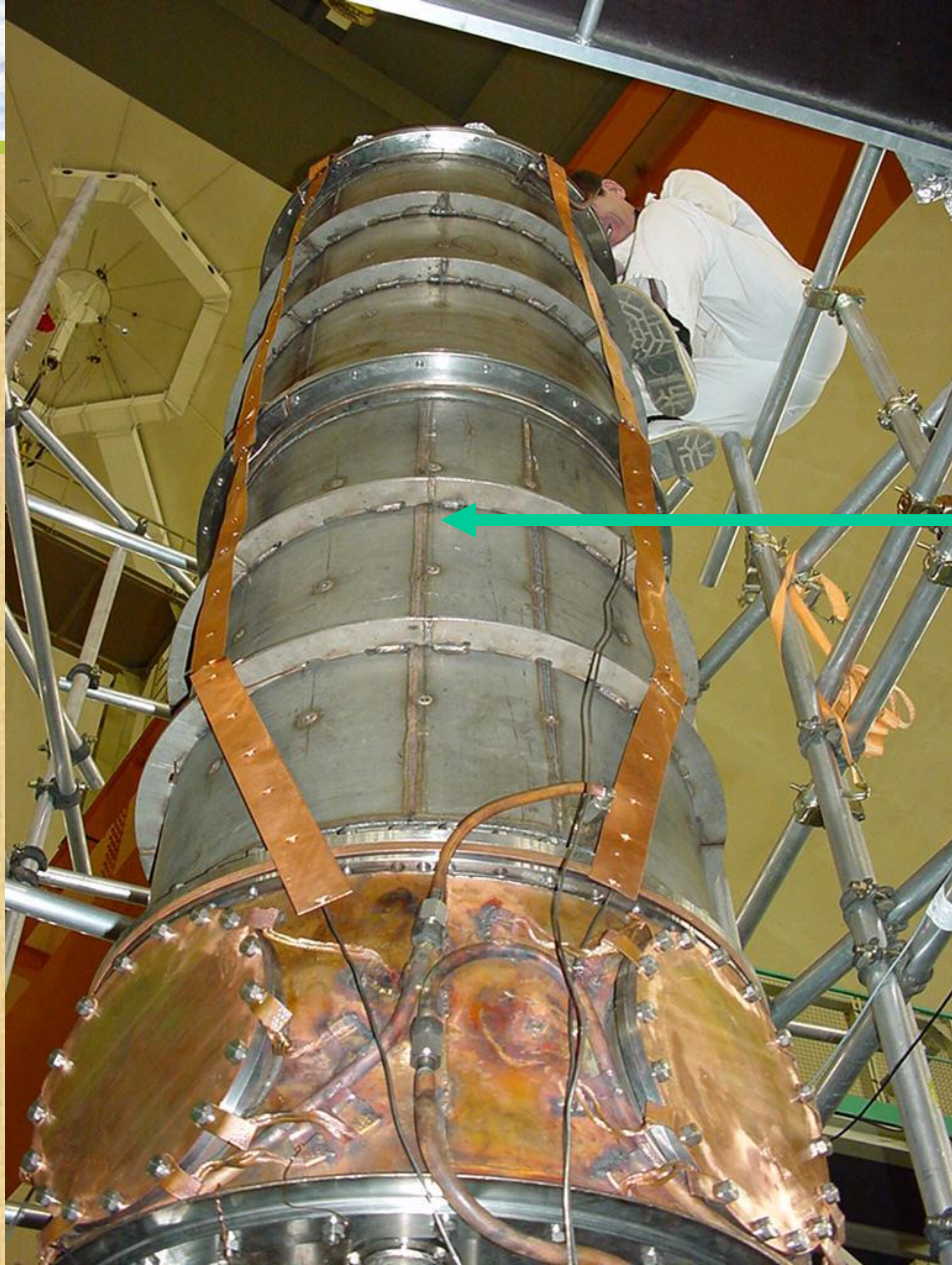
A sample can be placed here

The bellow of the sample changer is compressed

Spectrometer

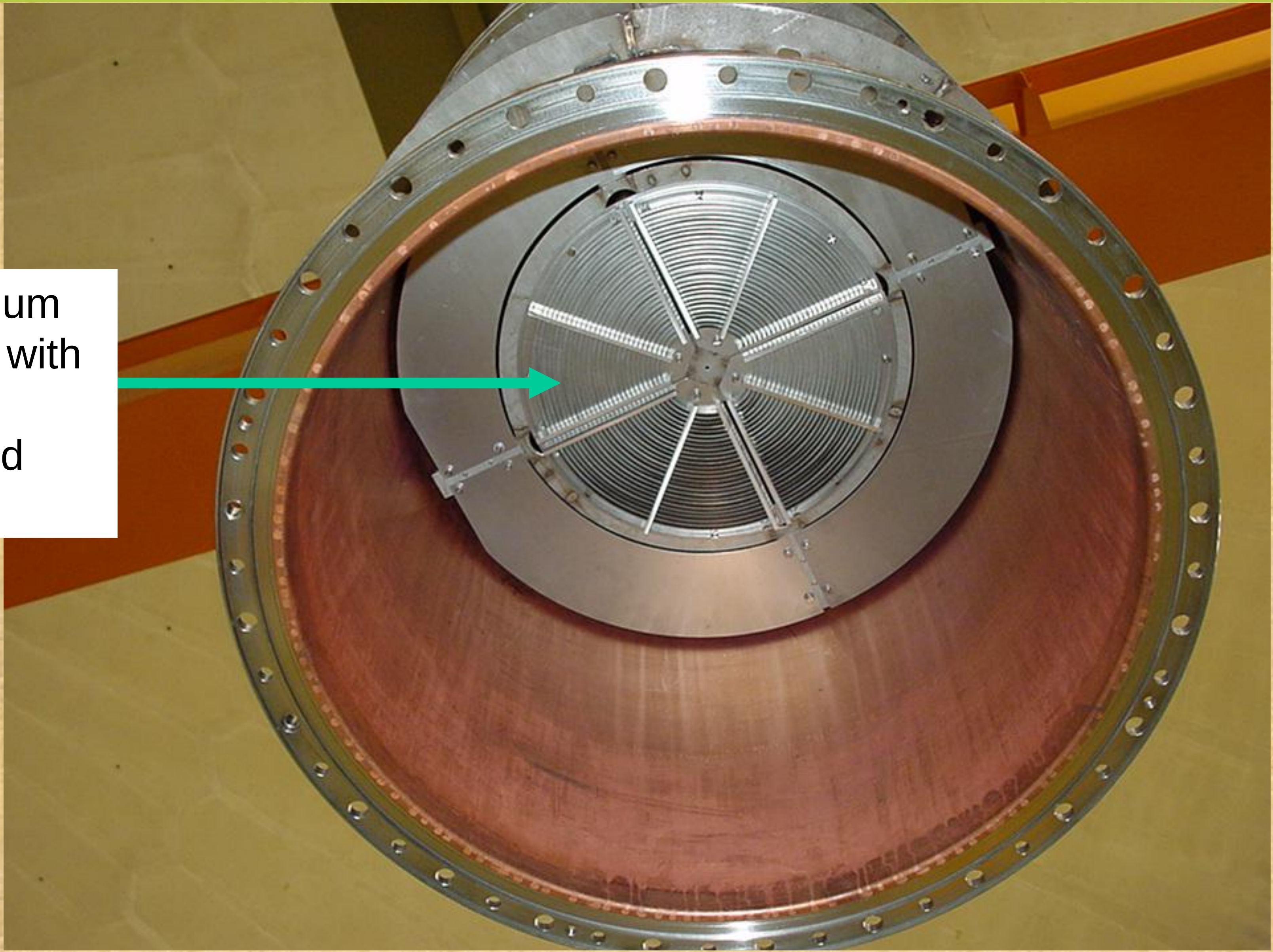


Spectrometer



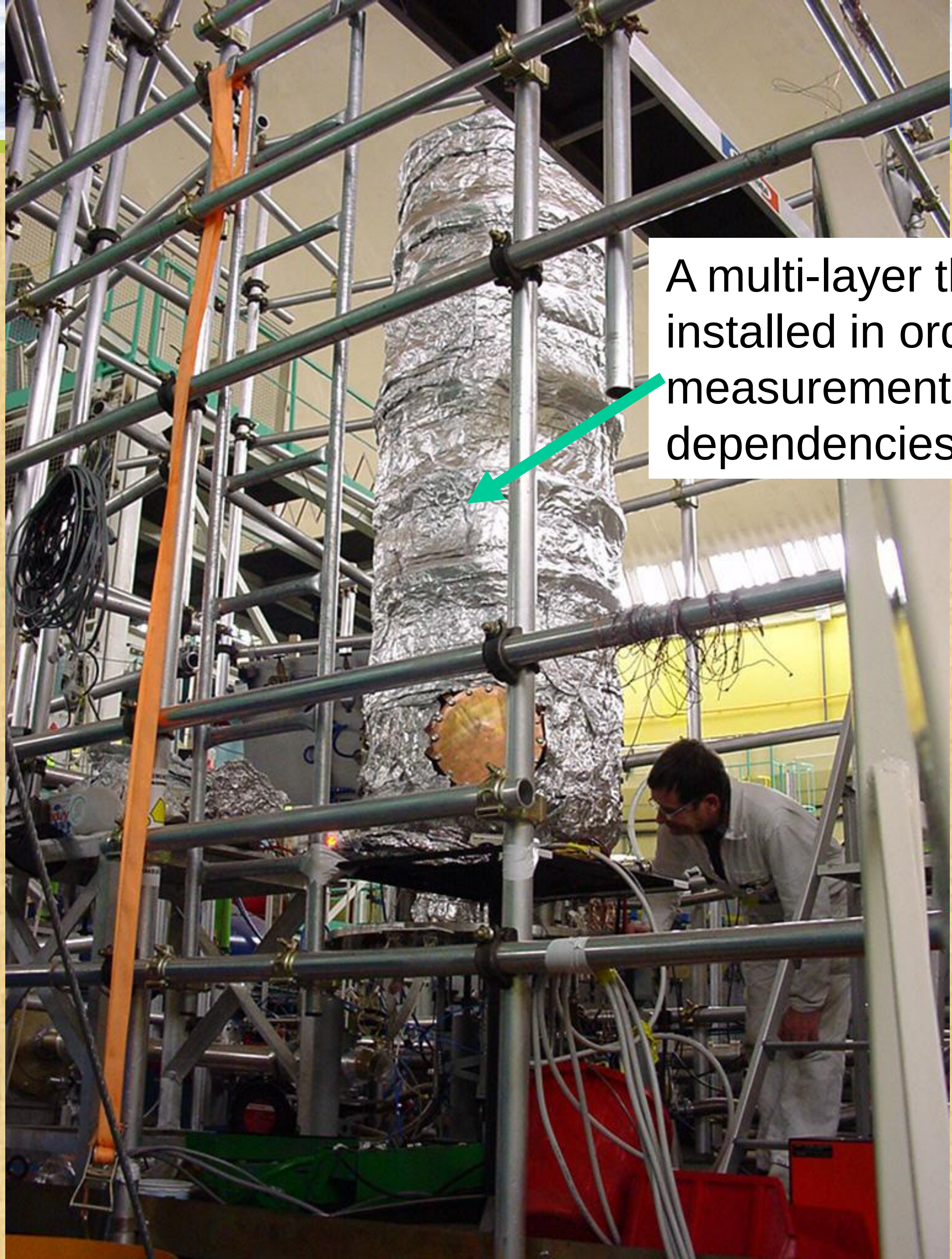
The external storage volume is assembled

Spectrometer



The titanium absorber with highly developed surface

Spectrometer



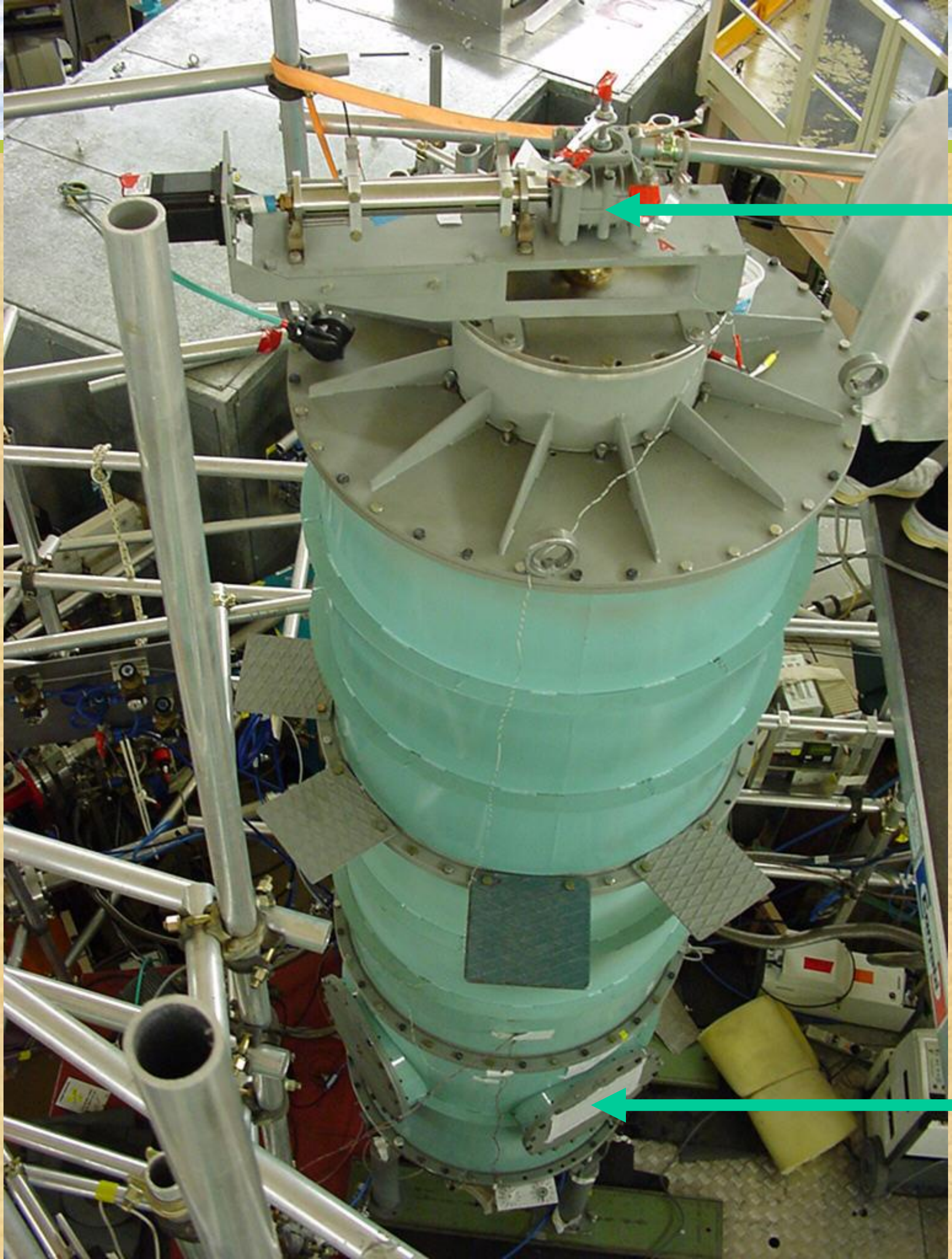
A multi-layer thermal screen is installed in order to allow for measurements of temperature dependencies

Spectrometer

The vacuum chamber

Spectrometer

The spectrometer is assembled

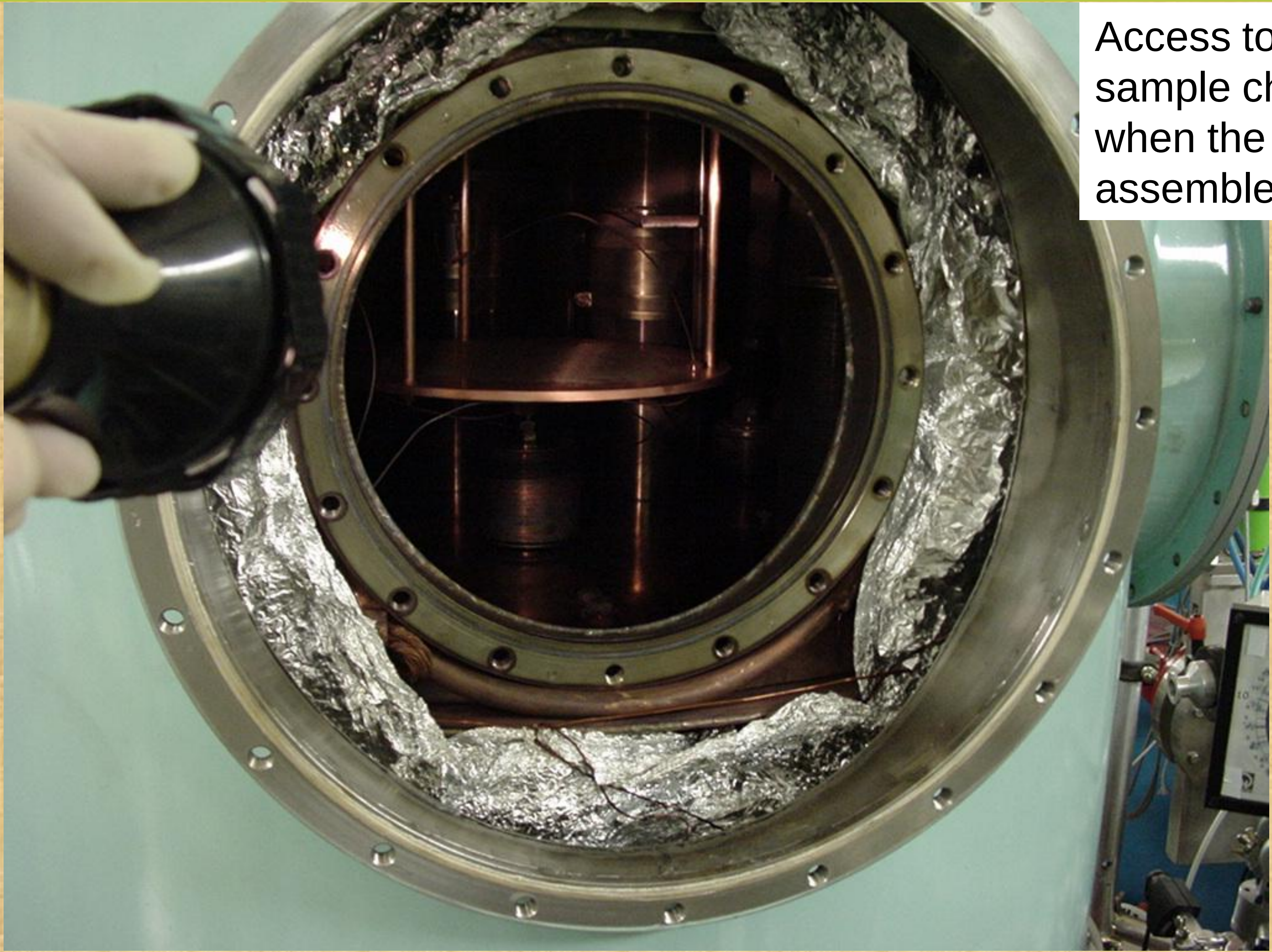


Movement of the absorber

Access to the sample changer

Samples

Spectrometer



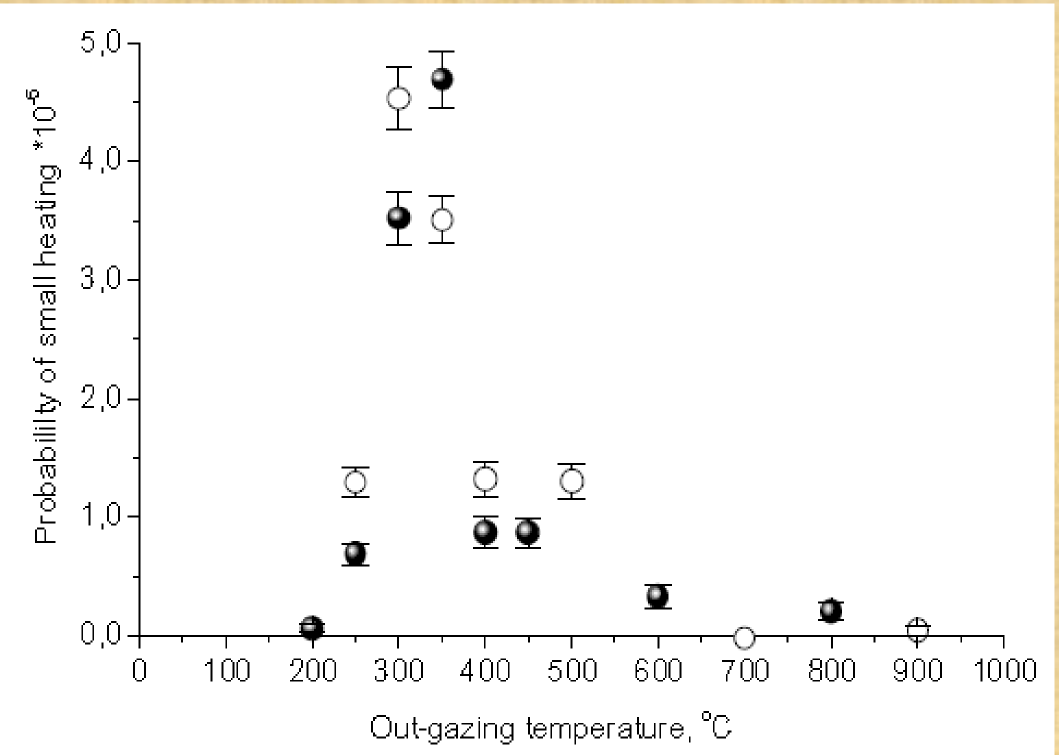
Access to the sample changer, when the setup is assembled

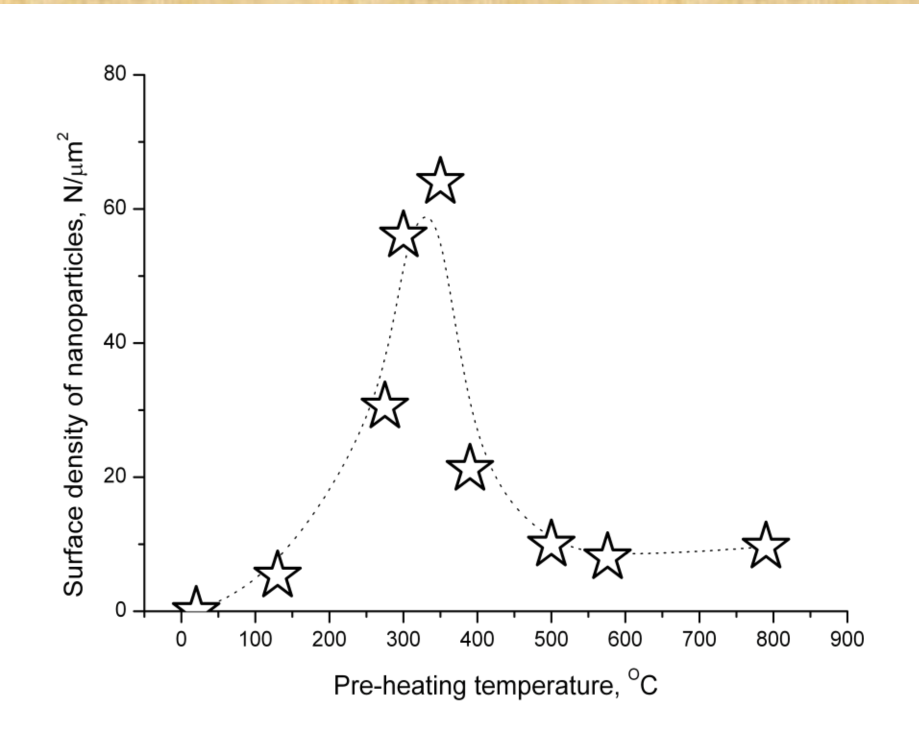
Spectrometer

Installation of a sample

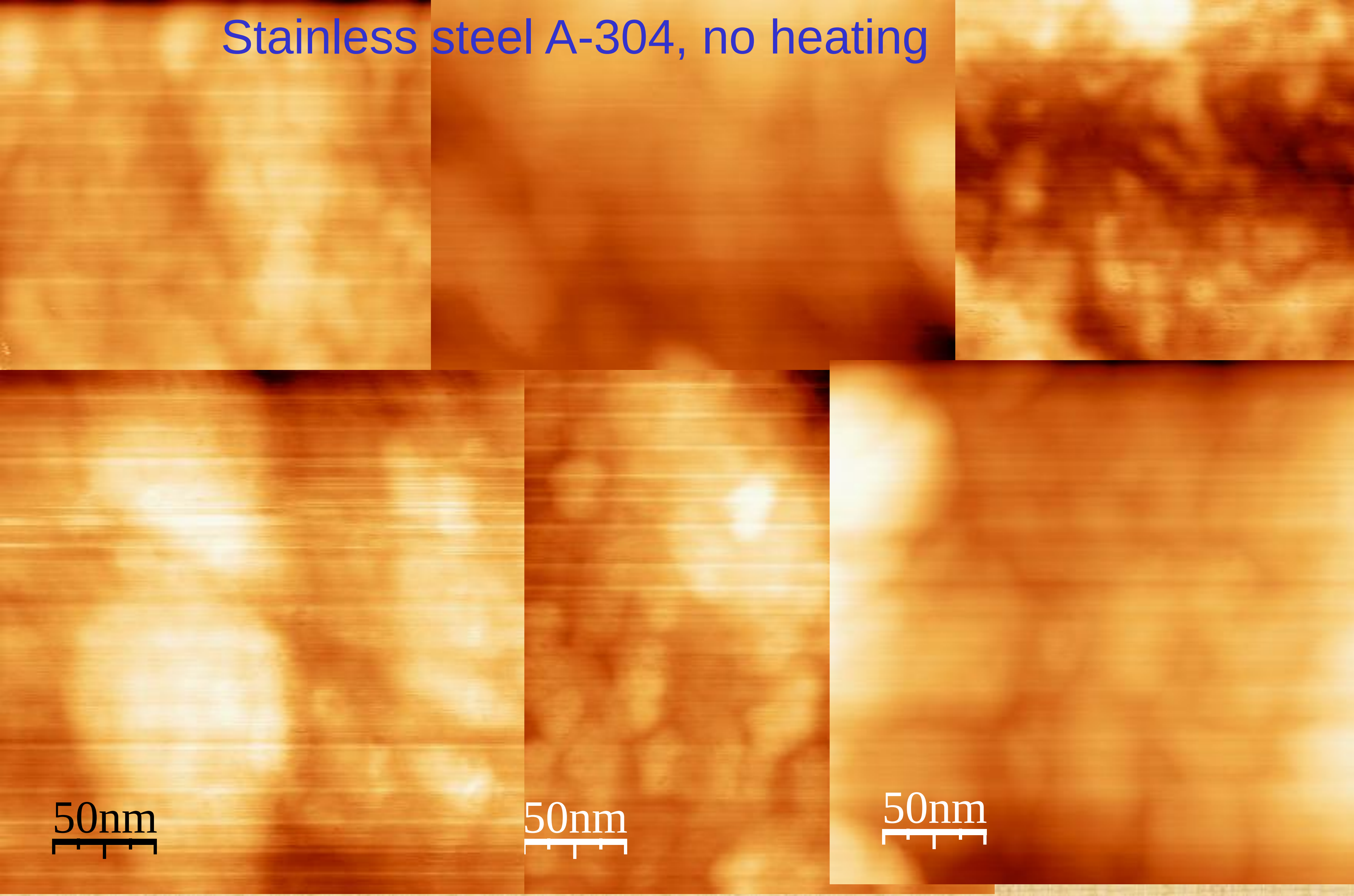
« Temperature resonance »

The probability of « small heating » of UCN (on the left side) and the population of nanoparticles of « right » size as a function of temperature of the surface outgasing

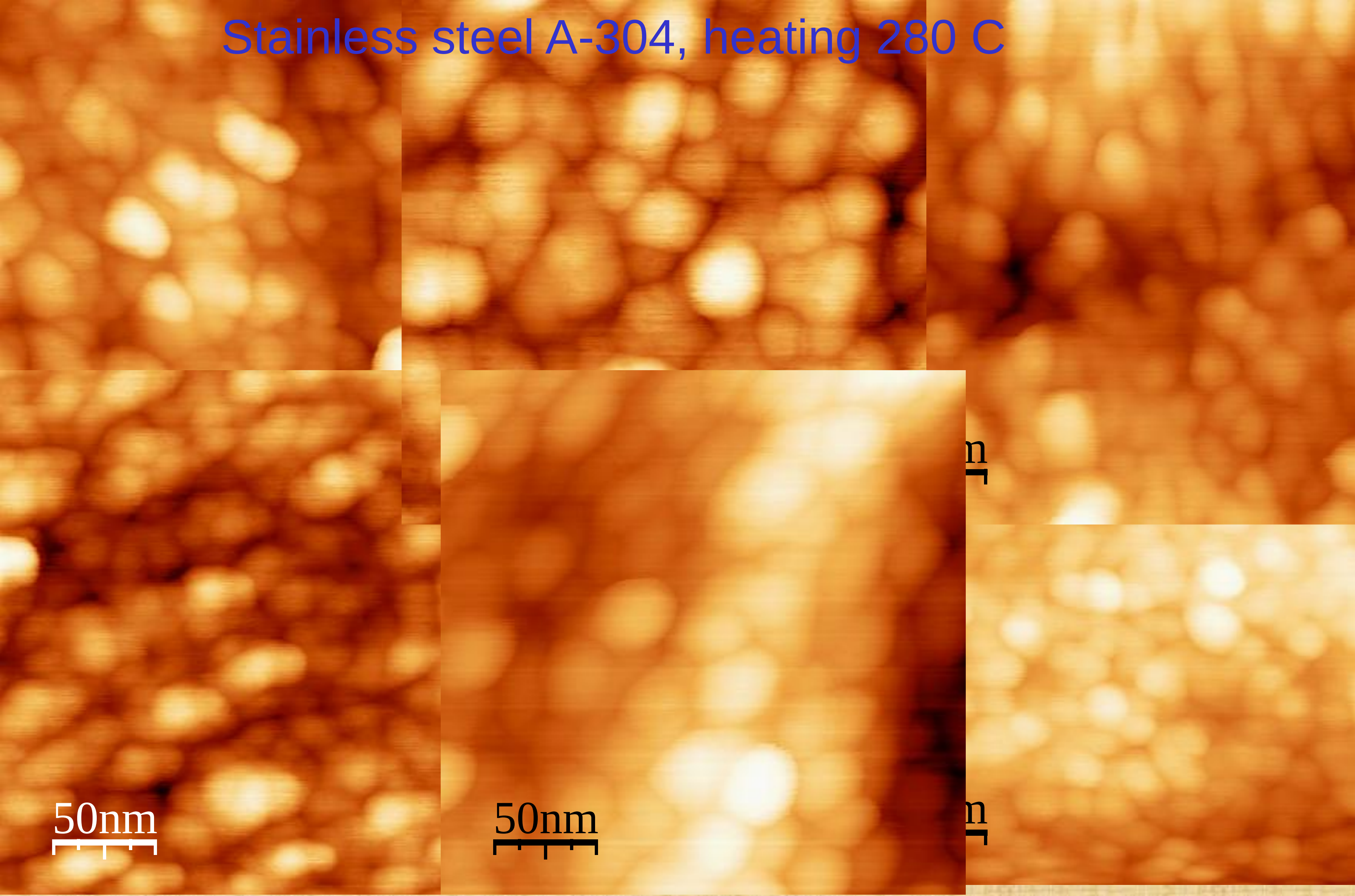




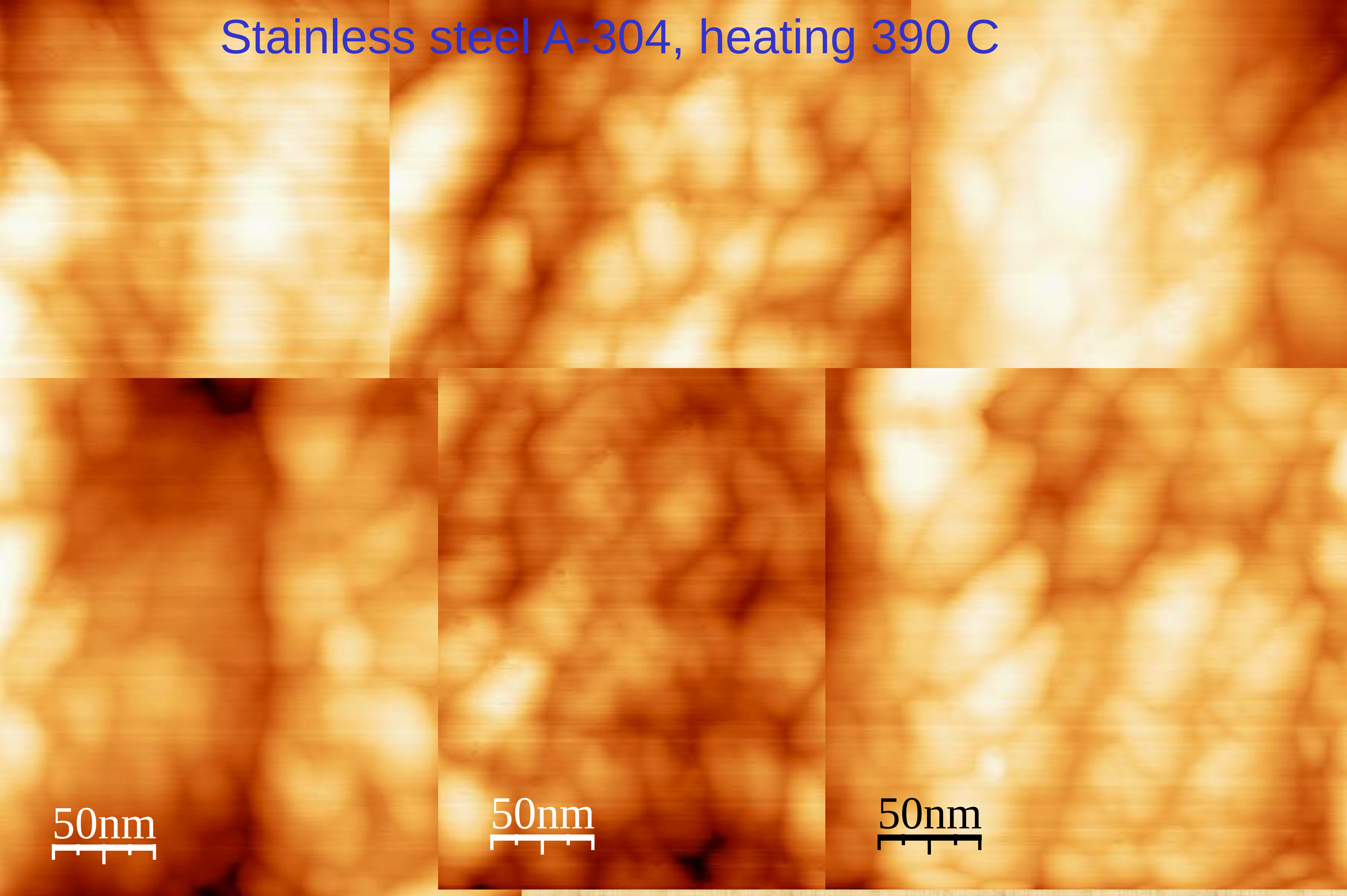
Stainless steel A-304, no heating



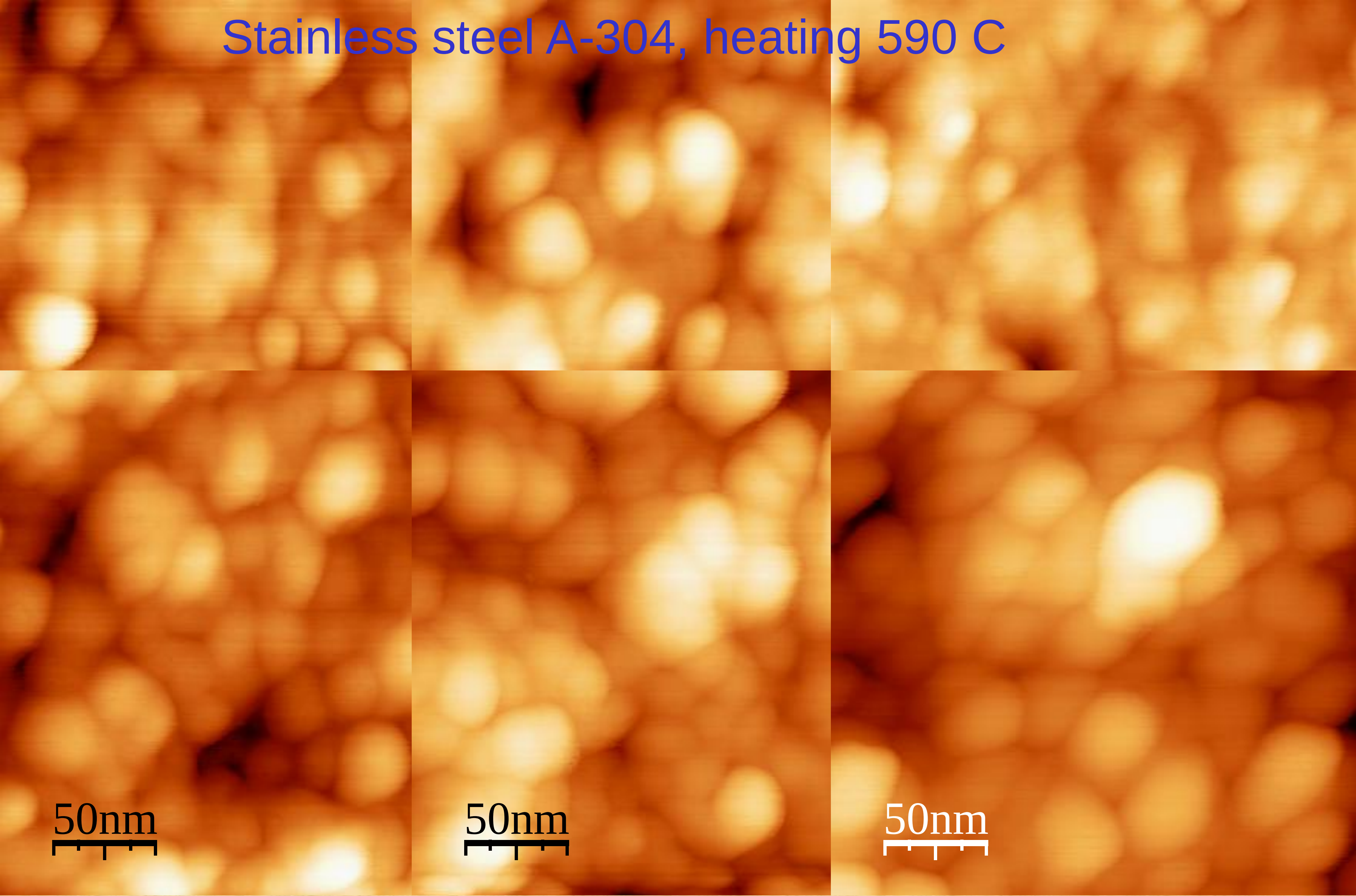
Stainless steel A-304, heating 280 C



Stainless steel A-304, heating 390 C

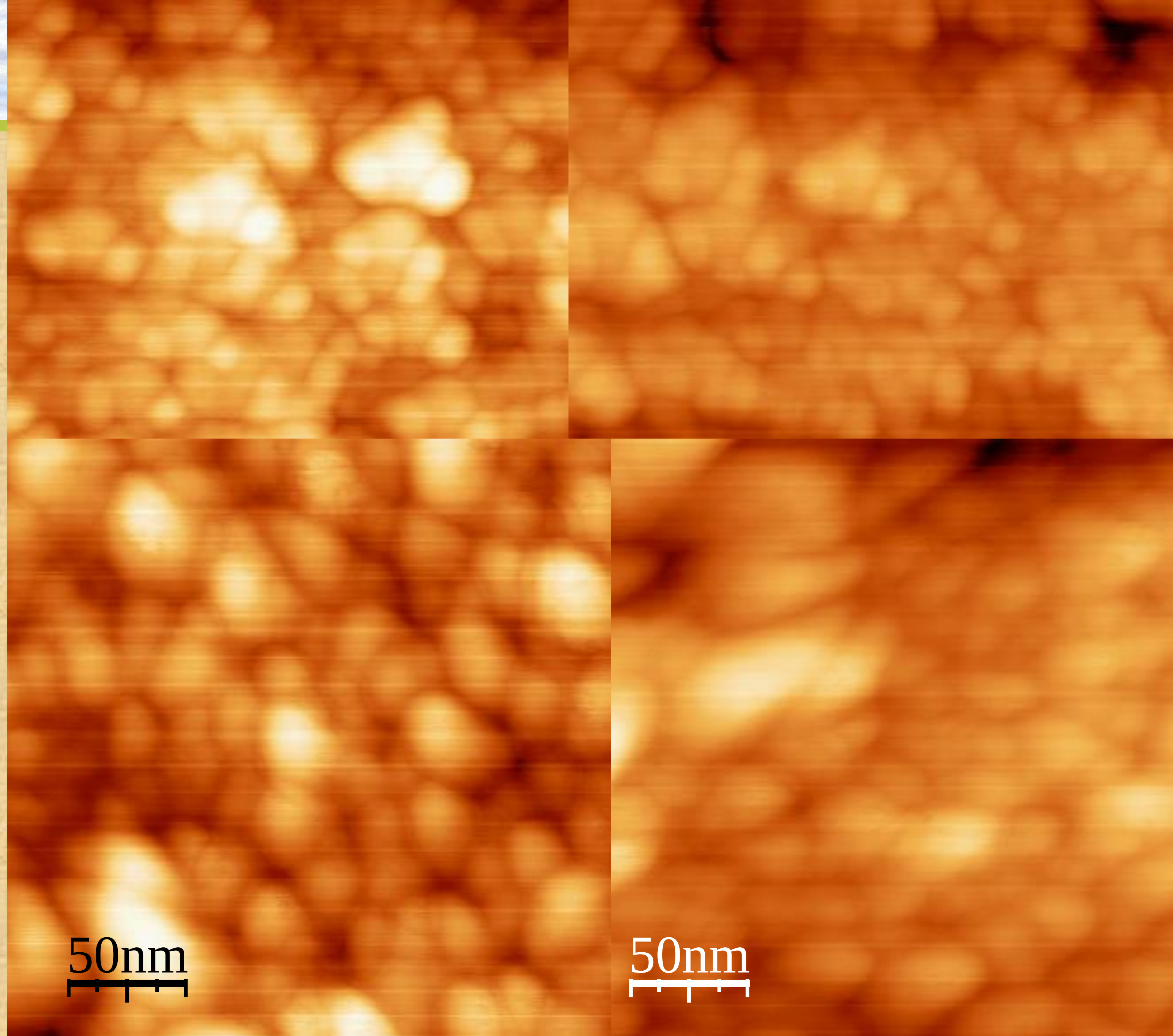


Stainless steel A-304, heating 590 C

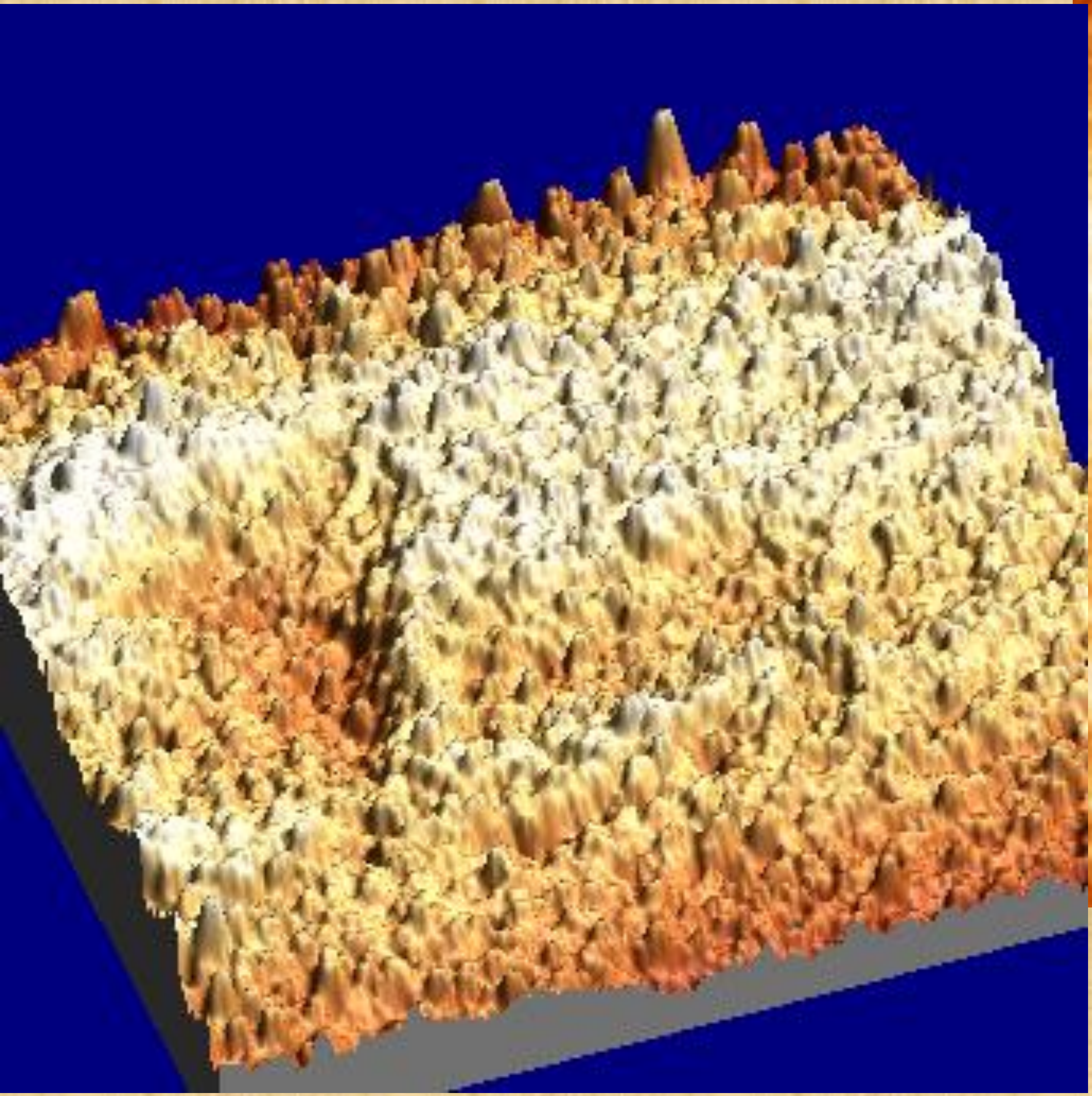


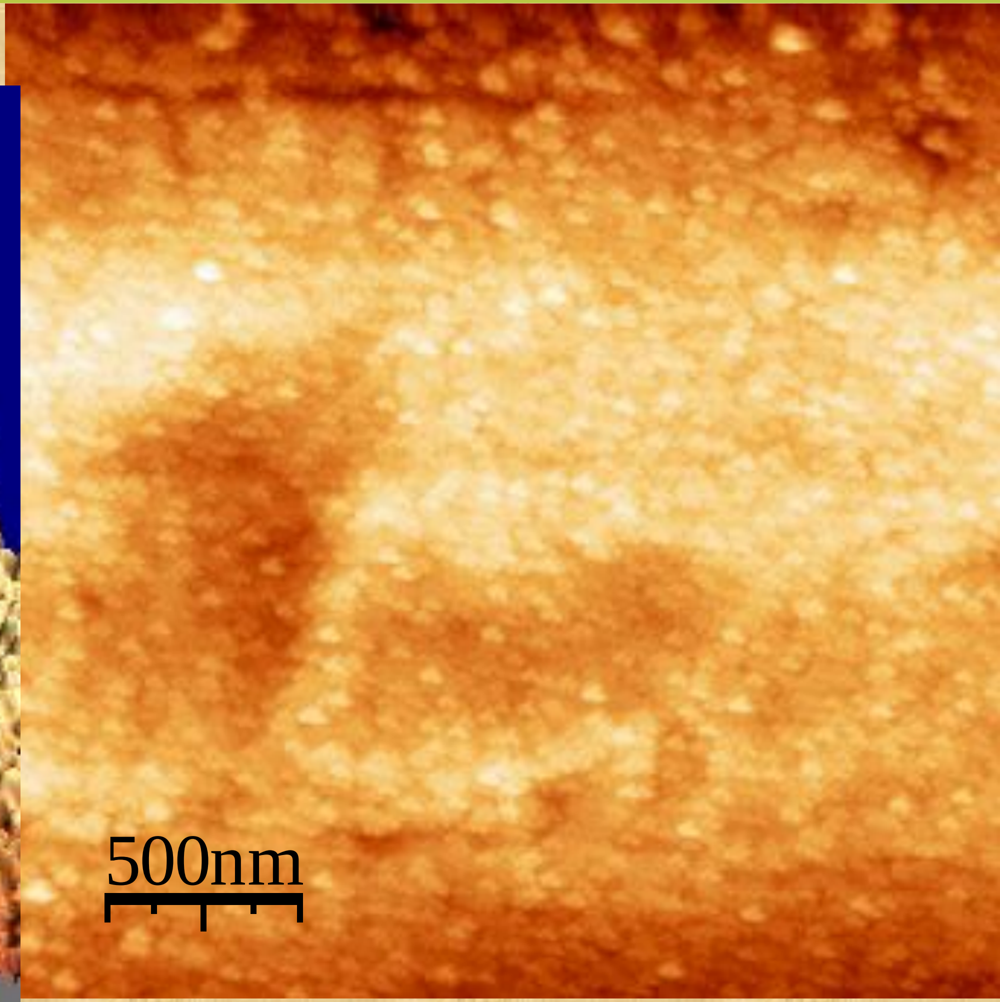
Copper,
heating 250 C

Copper,
heating 350 C

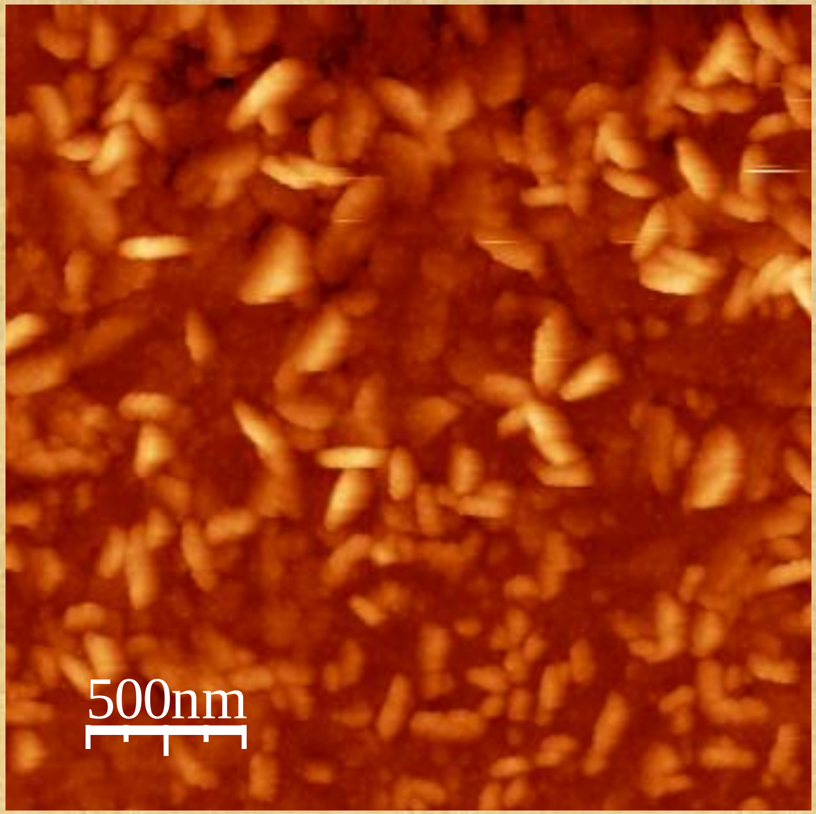


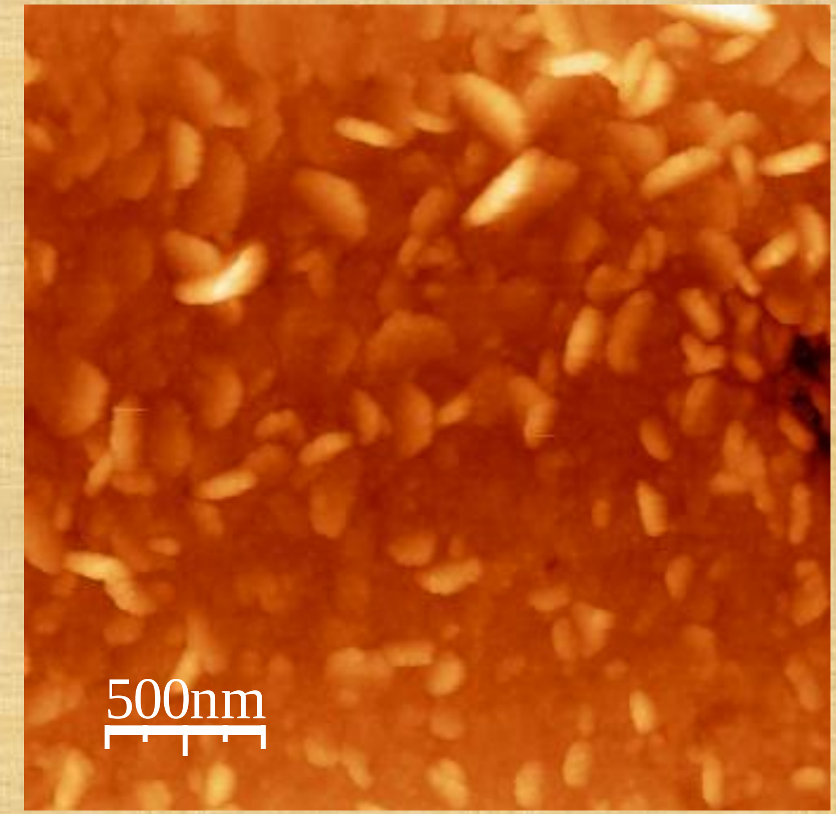
Copper, heating 250 C



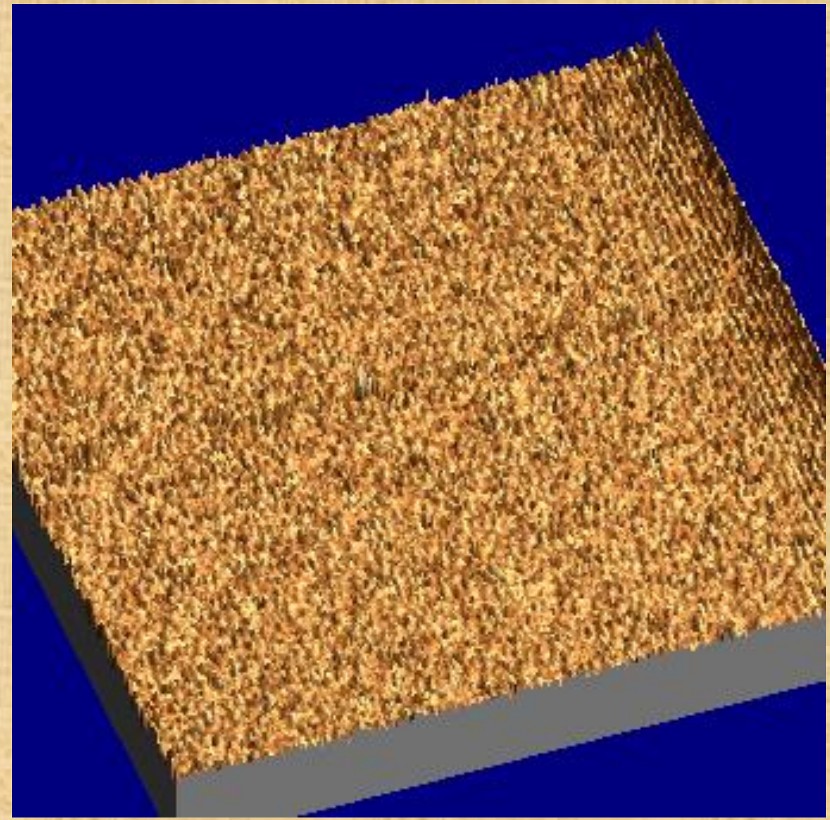


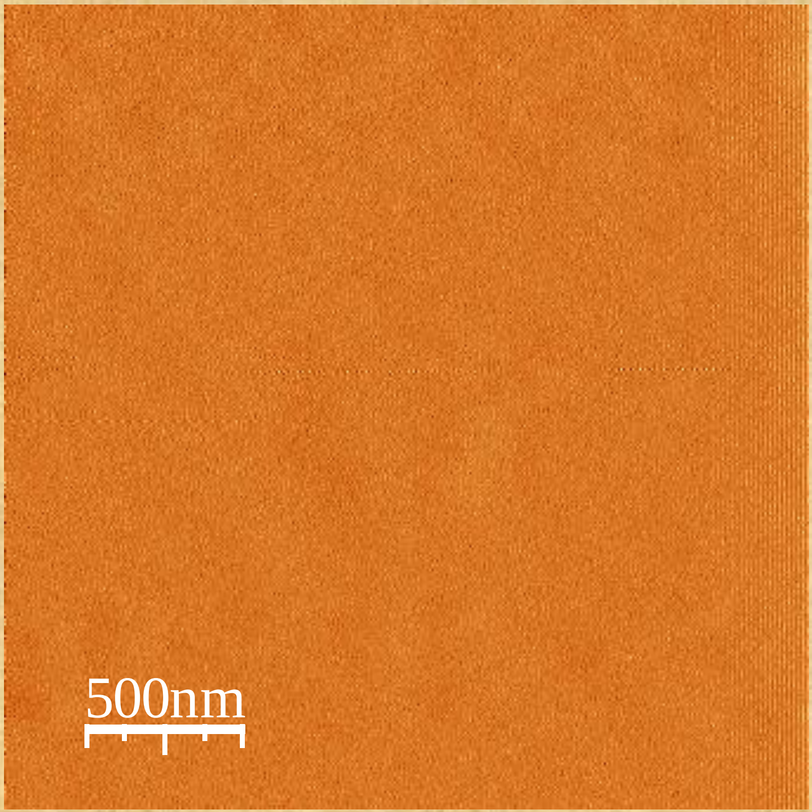
Lead, no heating



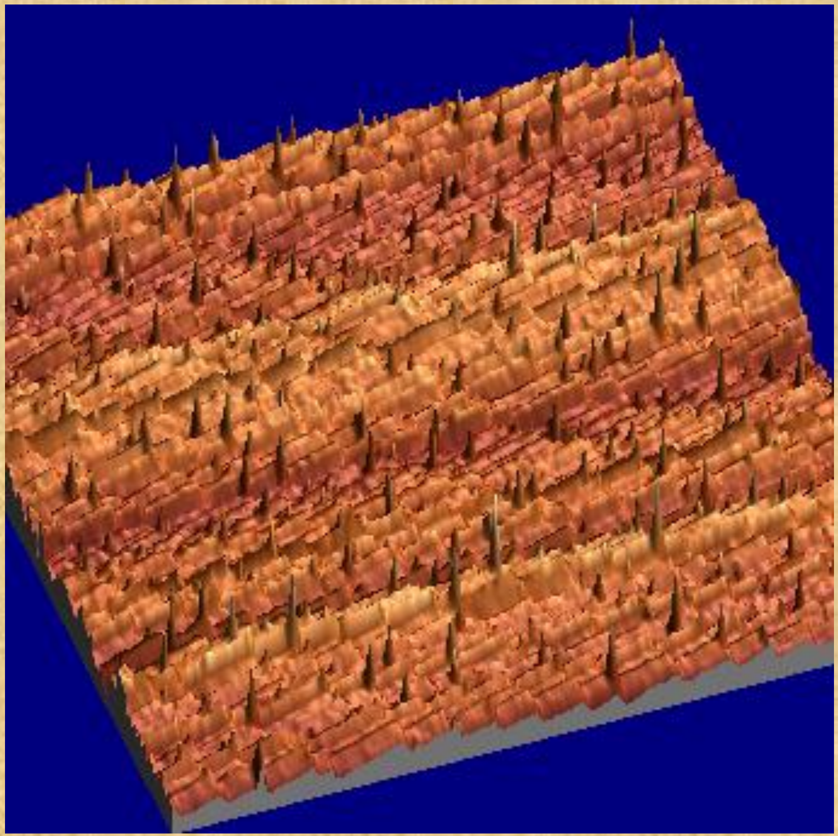


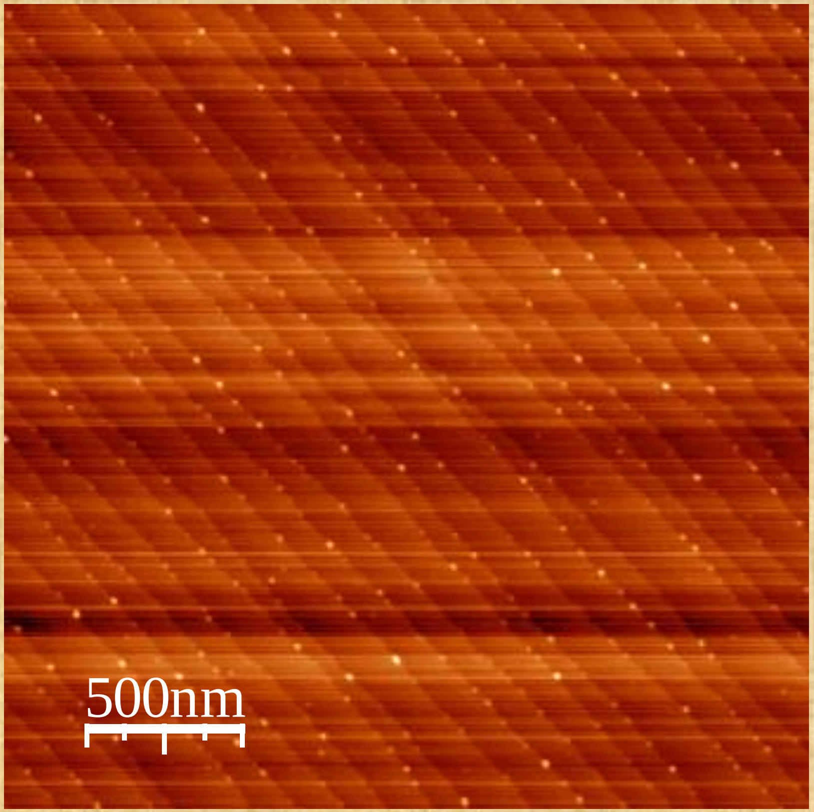
Polished sapphire, no heating



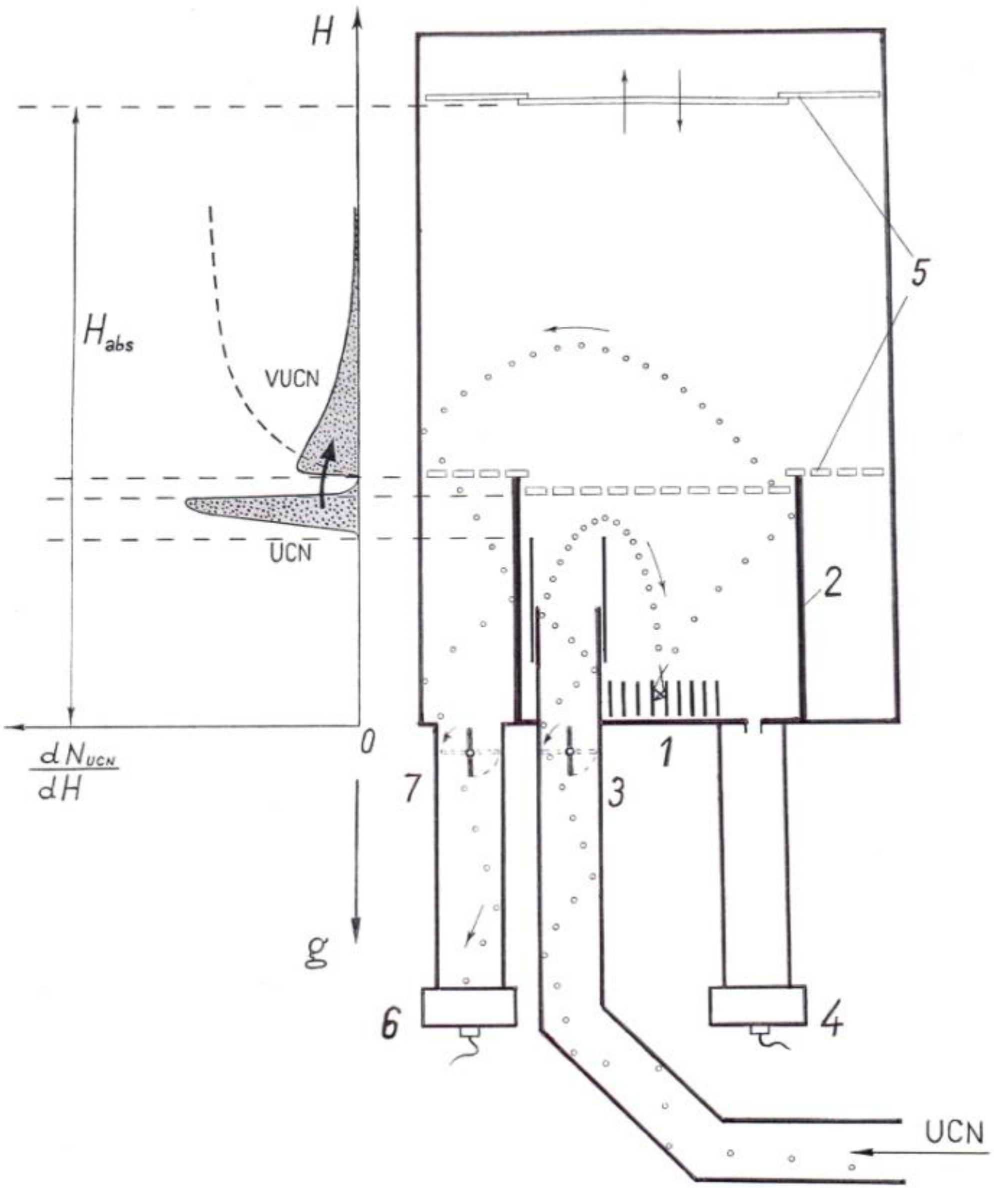


Polished sapphire, heating 1550 C



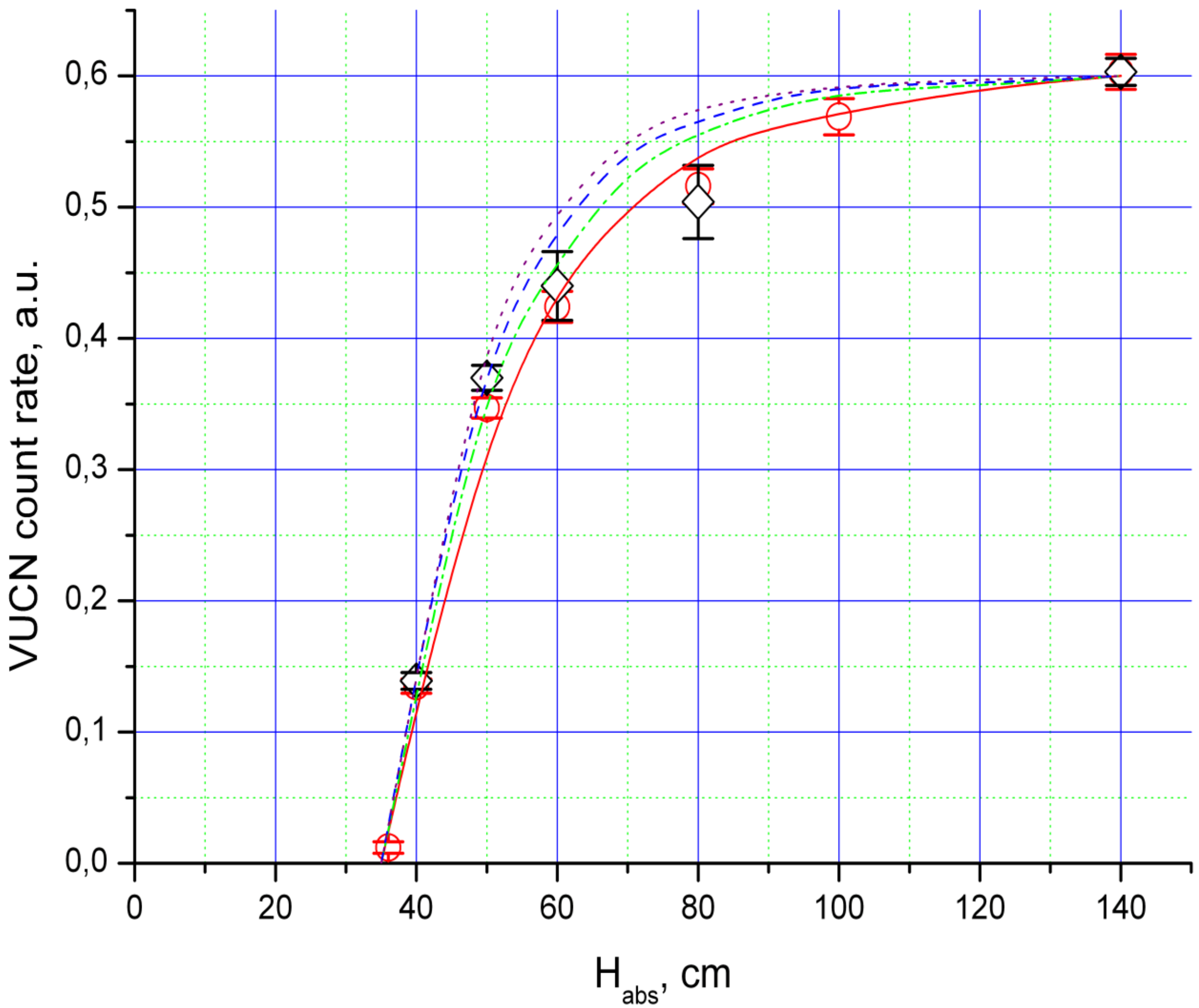


Experimental method; new measurements



Layout of the BGS gravitational spectrometer of the total UCN energy: (1) sample, (2) gravitational barrier, (3) entrance valve, (4) UCN monitor detector, (5) UCN absorber, (6) VUCN detector, and (7) exit valve. The principle of the procedure to measure small energy transfers is sketched in the insert on the left side. From bottom to top (in scale): initial differential UCN spectrum (the mean energy is 31 neV, the half-width of the spectral mono-line is 3 neV), a dead-zone of insensitive to VUCNs, the differential and integral (dashed line) spectra of VUCN. The differential efficiency of VUCN detection is calculated using precisely measured values of UCN and VUCN storage times as a function of their energy; decrease in the detection efficiency, caused by partial losses of neutrons in samples, is taken into account.

Integral VUCN spectra



-Circles show results measured with various solid nanoparticles: diamond, sapphire, copper.

-Rhombuses indicate data measured with a Fomblin oil sample.

-Four lines correspond to calculations of VUCN spectra on the Fomblin surface, within our model, for four hypothesizes on the size distribution of nano-droplets:

$(R/R_0)^{-l}\ l = 1; 2; 3; 4$

Simplifications of the model used

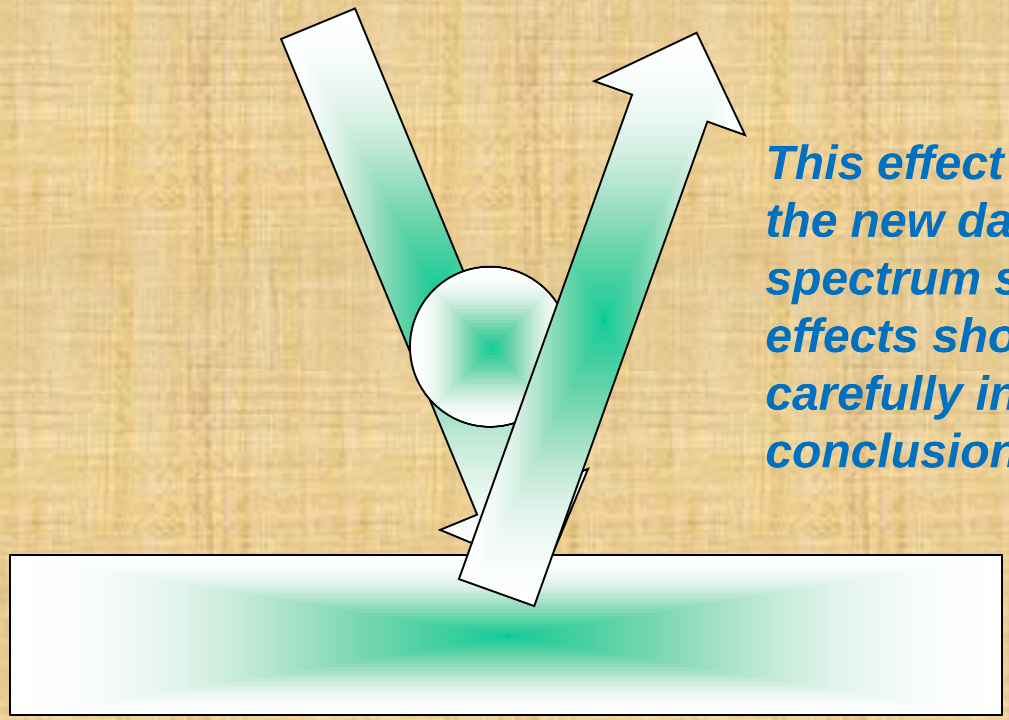
Neglected effects:

-***Rotations of nanoparticles;***

-***Non-sphericicity and non-uniformity of nanoparticles;***

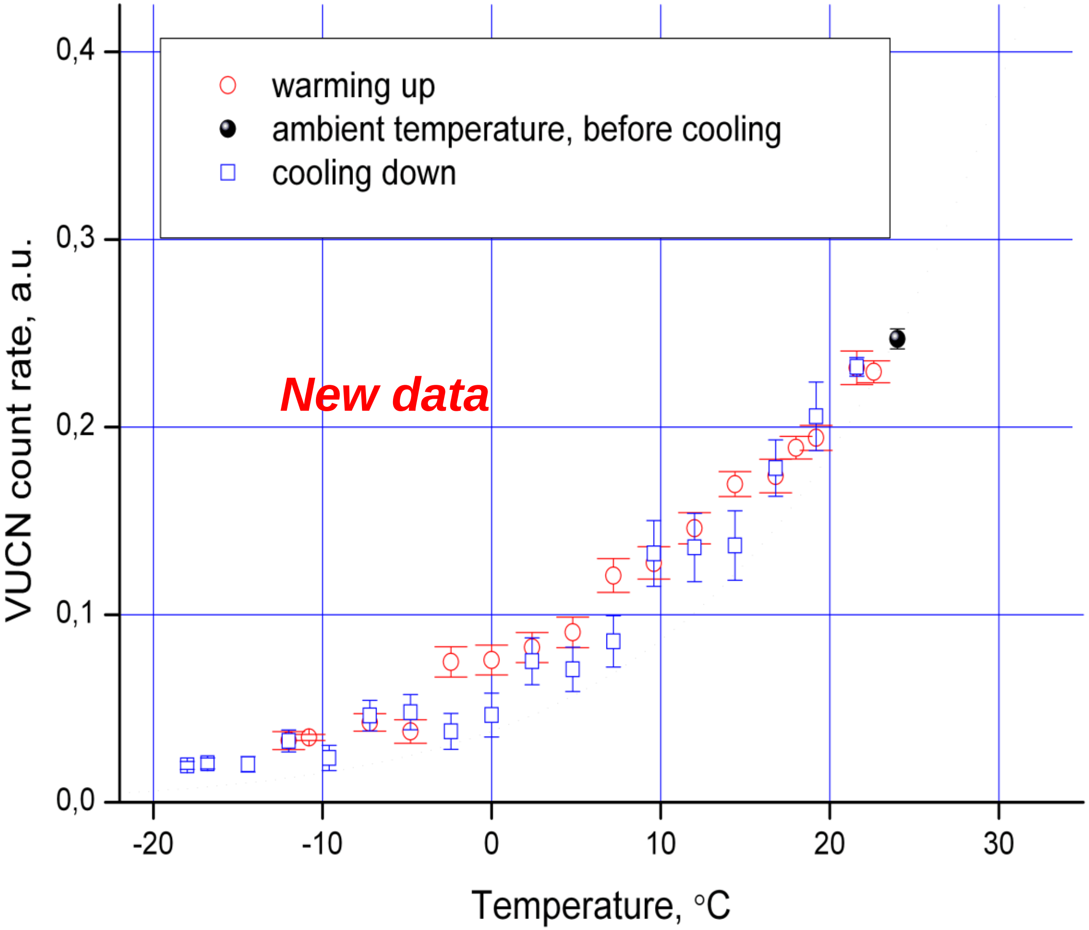
-***Interference of scattering on neighbour nanoparticles;***

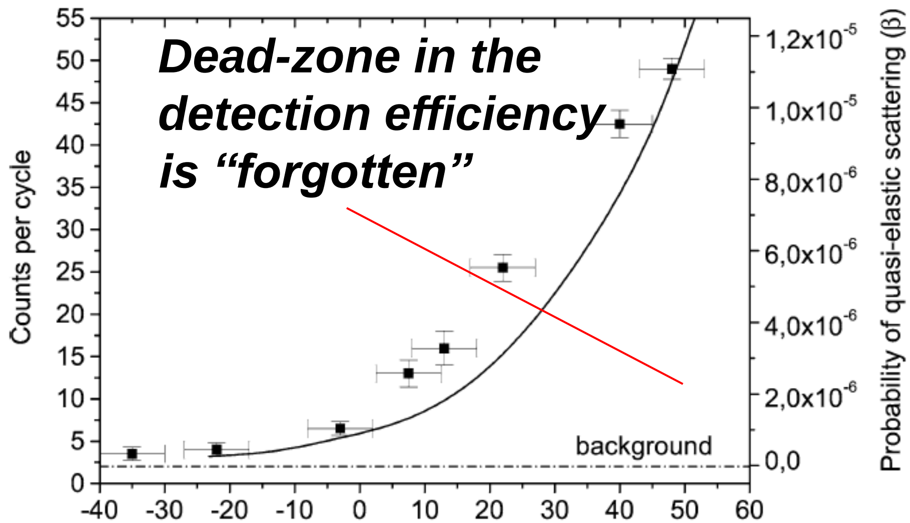
-***Consequent scatterings on one nanoparticle*.**

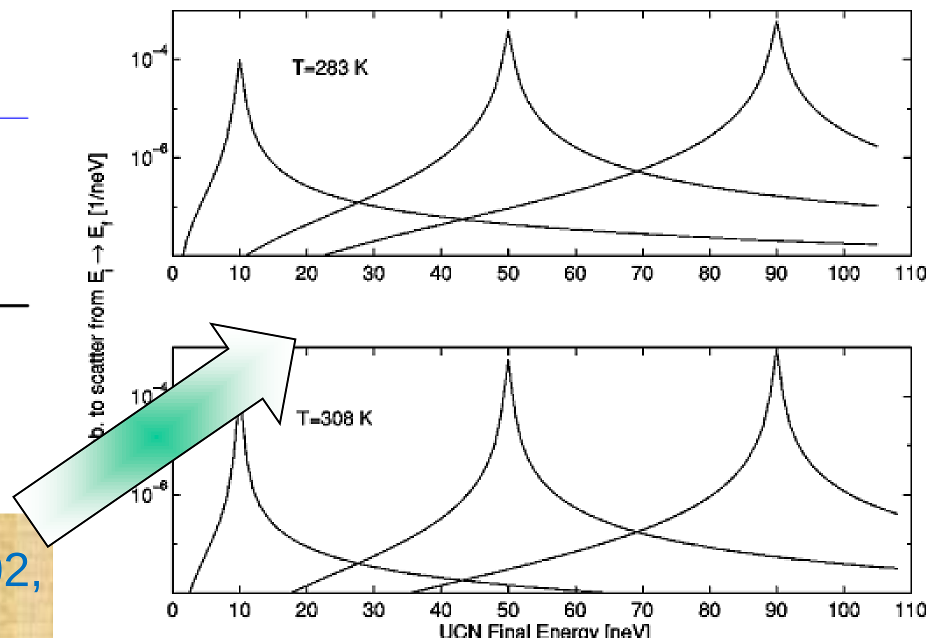


This effect is (probably) visible in the new data; it modifies the spectrum shape. However, other effects should be considered carefully in order to make final conclusions

Integral VUCN spectra







[**S.K. Lamoreaux, P.A., R. Golub**, *Phys. Rev. C* 2002, Vol. 66, 044309]

Applications

-*Studies of the vdW/CP interaction between nanoparticles and surface;*

-*Nanoparticle's mobility study (complementary to decorating surface defects, edges, boundaries, elastic strain fields);*

-*Surface chemistry;*

-*Knowledge of details of this process allows one making proper corrections to precision experiments with UCN, in particular to neutron lifetime experiments*

Analogous effects

-*Gravitational and centrifugal quantum states of UCNs and anti-hydrogen atoms*

Conclusion

1. Physical adsorption of nanoparticles/ nanodroplets is manifested in experiments with stored UCNs
2. It explains « small heating » of UCNs
3. It results to false effects in precision experiments with UCNs, in particular in neutron lifetime experiments
4. It can be used to study surface potentials