Atomic hydrogen gas at the surface of superfluid helium

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Abstract. We review recent experimental studies of spin polarized atomic hydrogen gas adsorbed on the surface of liquid helium.

1. Introduction
Spin-polarized atomic hydrogen adsorbed on the surface of liquid helium at low temperatures represents a unique weakly interacting two-dimensional gas, where one expects to find quantum degeneracy effects such as the phenomenon of Bose-Einstein condensation (BEC). In two-dimensional films of liquid helium a similar phenomenon has been observed, known as Kosterlitz-Thouless transition to a superfluid state. Comparing properties of the condensate in the weakly interacting two-dimensional hydrogen gas with true 3D BEC extensively studied in dilute alkali vapors, as well as with another extreme case of the strongly interacting helium liquid, would be of great interest and motivates the research in this field.

In this paper we discuss the latest experimental studies of two-dimensional hydrogen gas adsorbed on the surface of helium performed by our group at Turku. Comprehensive reviews of the atomic hydrogen studies have been written by Greytak and Kleppner [1] and by Silvera and Walraven [2]. More recent studies of the two-dimensional hydrogen gas have been reviewed by Walraven [3] and by Vasilyev and Jaakkola [4].

2. Properties of 2D hydrogen adsorbed on liquid helium
2.1. Hydrogen atom on the helium surface
Superfluid helium is a unique substrate for studies of adsorbed quantum gases. It is chemically inert and provides the smallest known atom-surface interaction. At temperatures below 300 mK $^4$He vapor pressure is negligibly small, and the space above the liquid can be considered as a good vacuum. Atomic hydrogen is the only substance known to remain a gas down to the zero temperature and not being dissolved into liquid helium. Being heavier $^3$He its chemical potential of -2.8 K inside $^4$He and normally at low temperatures these two isotopes of helium form a solution. The interaction potentials of hydrogen and $^3$He with the surface of $^4$He (fig. 1) support bound states with the density profiles depicted in fig. 2. Hydrogen has the smallest binding energy to the surface of liquid helium. On pure $^4$He it was found to be $E_a = 1.14$ K [6]. If $^3$He is added into the liquid, it occupies also surface states and this decreases the hydrogen adsorption energy to $E_a = 0.36$ K [6].
In experiments with 2D hydrogen a bulk H gas of typical densities $10^{12}$-$10^{15}$ cm$^{-3}$ is present above the surface being in a dynamic equilibrium with the adsorbed 2D H↓ phase. To find the relation between these two phases one has to equate the chemical potentials of the 3D and 2D Bose gases [7]. At the densities considered the bulk gas is non-degenerate and one can use the classical chemical potential $\mu_3 = T \ln(n \Lambda^3)$ with $\Lambda$ being the thermal de Broglie wavelength. Aiming at quantum degeneracy of the surface gas we have to take into account statistical effects and interatomic interactions. The latter are often represented by the mean-field interaction energy $\tilde{U}_\sigma$ where $\sigma$ is the surface density. Then we have for the 2D gas the expression $\mu_2 = T \ln[1 - \exp(\sigma \Lambda^2)] - E_a + g \tilde{U}_\sigma$. Here the two-body correlator $g = 2 - \sigma_{cond}/\sigma$ takes into account the appearance of the condensate with surface density $\sigma_{cond}$. Adsorption isotherms calculated for several values of the surface temperature are presented in fig. 3. One can see that the change of the correlation properties at BEC leads to a decrease of the interaction energy and an increase of the adsorbed gas density. For small enough values of $\sigma$, 2D gas is non-degenerate and the interaction energy can be neglected. Then, the surface density can be explicitly expressed through the bulk density by using the classical adsorption isotherm

$$\sigma = (T_g/T_s)^{3/2} n \Lambda \exp(E_a/T).$$  (1)
The factor \((T_g/T_s)^{3/2}\) takes into account a possible difference in the respective temperatures \(T_g\) and \(T_s\) of the bulk and surface gases.

The adsorbed hydrogen atoms interact with ripplons, thermal excitations of the surface of the helium film. The rate of momentum and energy exchange between \(\text{H}_1\) and ripplons has been calculated by Zimmerman et al. \[8\]. In the temperature range 0.1-0.3 K the characteristic momentum relaxation time of the hydrogen atom due to emission and absorption of ripplons is of the order \(10^{-8}\) s, i.e. much shorter than the surface residence time of the atom. This implies that the surface \(\text{H}_1\) gas is effectively thermalized by ripplons. These in turn interact with phonons, the bulk excitations of the film. It has been calculated \[9\] that the process of two-phonon inelastic scattering controls the exchange of energy between these two systems, and the heat flux from the ripplons of temperature \(T_r\) to the phonons of temperature \(T_p\) is a very strong function of temperatures, \(Q_{rp} = 8.4 \times 10^3 \text{[W m}^{-2}\text{ K}^{-20/3}](T_r^{20/3} - T_p^{20/3})\).

2.2. Interactions between atoms

The hyperfine level diagram of a hydrogen atom in a magnetic field is illustrated in fig. 4. Atoms in the two lower states \(a\) and \(b\) are high-field seekers and represent the gas of \(\text{H}_1\) considered in this paper. The exchange interaction between atoms during collisions depends on the direction of their electron spins and is described by well-known singlet and triplet potentials \[10\]. In \(\text{H}_1\) the thermal de Broglie wavelength \(\Lambda\) is normally much larger than the s-wave scattering length \(a_s\). This condition defines the cold collision regime with the s-wave being the main scattering channel. The mean field exchange interaction energy is positive for both singlet and triplet interactions. In the case of the 3D gas it is equal to \(E_{ex} = 4\pi\hbar^2 a_s^{s,t} n/m\), with \(a_s^s \approx 0.074\) nm for the triplet potential and \(a_s^t \approx 0.022\) nm for the singlet potentials \[11\]. In the adsorbed \(\text{H}_1\) gas the delocalization length of the atoms in the direction normal to the surface is \(l = h/(2mE_a)^{1/2} \approx 0.49\) nm. This is comparable with the characteristic length of the interatomic potential \(r_0 \approx 0.35\) nm, and therefore the collisions between the atoms acquire a quasi-2D character \[12\]. The effective scattering length approach can be still used in this case with the exchange interaction energy being proportional to the surface density, \(E_{ex} = \tilde{U}\sigma\), where \(\tilde{U} \approx 2(2\pi)^{1/2}\hbar^2 a_s^{s,t}/l\) \[12\]. It has been observed in experiments with alkali atoms \[13\] that the difference of \(a_s^t\) and \(a_s^s\) may lead to a cold collision frequency shift (also known as the "clock shift") of the atomic transitions. Using the above numerical values of the scattering lengths, we estimate the cold collision shift of the \(b \rightarrow c\) (\(a \rightarrow d\)) ESR lines to be \(\Delta B_{ex} \approx 10^{-11}\text{[cm}^2\text{]}\sigma\). This value is an order of magnitude larger than the shift of the ESR lines due to the average dipolar field in the 2D system \[14\]. In both cases the shift is proportional to the surface density, but the difference is that the dipolar interaction is anisotropic and depends on the orientation of the surface with respect to the polarizing magnetic field. The latter effect was observed in the experiments of Hardy and coworkers \[14\]. A third shift type associated with surface adsorbed \(\text{H}_1\) atoms and known as the "wall shift", has been studied experimentally by NMR \[15\] utilizing the \(a \rightarrow b\) (fig. 4) transitions. Van der Waals forces binding the atoms to the surface cause a deformation of the electron wavefunction and reduce the strength of the hyperfine interaction. The corresponding shift of the hyperfine levels is independent of the surface density but depends on the orientation and strength of the polarizing magnetic field. For a 7.62 T magnetic field parallel to the surface the wall shift was found to be \(\delta_w \approx 22\) kHz \[15\] (\(\Delta B_w \approx 8\) mG), which is negligibly small compared to the exchange and dipolar shifts of the ESR transitions in the experimental conditions considered here.

2.3. Recombination and relaxation

The decay mechanisms of \(\text{H}_1\) include one- and two-body relaxation, two-body exchange recombination and three-body dipole recombination \[2\]. The exchange recombination occurs when one of the colliding atoms is in the hyperfine state \(a\) (\(F = 0, m_F = 0\)). This state has
a small admixture of the opposite electron spin orientation, leading to a finite probability of depolarization of the electron spin and to a subsequent recombination in binary collision on the walls. Such a preferential recombination of the \(a\) state leads to the sample containing atoms in the "pure" state \(b\) \((F = 1, m_F = -1)\) only (fig. 4). Relaxation from \(b\) to \(a\) is then becoming a bottleneck for the decay. One possible mechanism of such relaxation is due to interaction of the atoms with microscopic magnetic impurities present in the walls of the sample cell and is therefore often called "impurity relaxation". It has been also considered that eddy currents induced by the thermal motion of the atoms along the surface may induce spin flips. A basic remedy to eliminate one-body relaxation in \(\text{H}_\downarrow\) is to coat all metallic surfaces inside the sample cell with dielectric materials. This is typically done by lining the surfaces, in addition to the liquid helium film, with epoxy or plastic foil, and with a solid \(\text{H}_2\) layer resulting from the recombination of the \(\text{H}_\downarrow\) gas.

The rate of three-body dipole recombination is proportional to the third power of density and this mechanism dominates at high surface coverage. It is expected to be the main obstacle to the achievement of high \(\sigma\). There is a remarkable difference in the behavior of the recombination rate probabilities with the appearance of a condensate. Due to identical particle effects in the condensate the probability of a \(N\)-body process is suppressed by \(N!\), thus decreasing the rate of three-body processes by a factor of 6. Two-body exchange recombination involves distinct atoms and should not be influenced by the condensate formation. The decrease of the three-body recombination rate attributed to the appearance of the condensate in 2D \(\text{H}_\downarrow\) gas was observed at Turku [19].

3. Thermal compression experiments

The \(\text{H}_2\) molecules formed in recombination events appear in one of the upper excited rotational-vibrational states \((J = 3, v = 14)\) lying \(\sim 70\) K below the continuum of the singlet potential. This energy is released immediately in the recombination event, and a part of it goes to the excitations of the helium film, ripplons or phonons. The rest is carried away by the molecule and then gradually released in subsequent collisions with the sample cell walls. Such a mechanism has been confirmed in experiments [16, 17], and the fraction \(f\) of the energy submerged into the film directly at the recombination cite was found to be relatively small \(f \lesssim 2\%\). This fact makes it profitable to use local compression where the 2D gas is compressed at a small area on the wall of the sample cell [18, 7].

Two methods of local compression of adsorbed \(\text{H}_\downarrow\) have been implemented. They both rely on the strong exponential enhancement of the surface density defined by the adsorption isotherm (1). In thermal compression [16, 21], the temperature \(T_s\) of a small spot on the sample cell wall is lowered well below the rest of the cell. In magnetic compression [19, 20] \(\sigma\) is boosted by the factor \(\exp(\Delta B/T_s)\) at a local maximum of the magnetic field on the surface. Largest values of the quantum degeneracy parameter \(\varpi \equiv \sigma \Lambda^2 \approx 9\) were achieved by the magnetic compression method. However, the strong magnetic field gradients used in the magnetic compression create serious difficulties for direct diagnostics of adsorbed \(\text{H}_\downarrow\). The larger sample size and the very much higher homogeneity of the field make thermal compression well suited for direct studies of adsorbed \(\text{H}_\downarrow\) where electron-spin and nuclear magnetic resonance detection methods ESR and NMR are utilized.

A scheme of the sample cell used in the thermal compression experiments at Turku is presented in fig. 5. Hydrogen atoms are generated in a low temperature dissociator and transferred to the sample cell located in a magnetic field of 4.6 T. The sample cell is thermally pinned to the mixing chamber of a dilution refrigerator and can be cooled down to 80 mK. The thermal link is adjusted to allow a sensitive measurement of the recombination heat released in the sample cell by monitoring the feedback power of the temperature controller of the cell. The walls of the sample cell are covered with a superfluid film of pure \(^4\text{He}\) or a mixture of \(^3\text{He}\) and
4\textsuperscript{He}. By adjusting the level of liquid helium at the bottom of the cell we can open or close the line connecting it to the dissociator and seal off the gaseous H\textsubscript{↓} sample in the cell. Thermal compression is performed on a 6 mm diameter cold spot, thermally insulated from the rest of the sample cell with a 20 µm Mylar foil. For cooling the cold spot we use a part of the dilute \textsuperscript{3}He-\textsuperscript{4}He mixture from the mixing chamber of the dilution refrigerator. This coolant, the lowest temperature of which is $T_m = 50 \text{ mK}$, flushes the upper surface of the Mylar foil. Such a method allows rapid changes and a precise control of the coolant temperature up to 150 mK. The cold spot is located in a maximum of the magnetic field $H_1$ of a Fabry-Perot resonator connected to a mm-wave bridge of an ESR spectrometer. The latter operates at 127 GHz and has the detection limit of $10^9$ atoms at the excitation power of the order of several picowatts [22]. The excitation power is kept that low in order to minimize the disturbances caused by the depolarization and subsequent recombination of 2D H\textsubscript{↓} when detecting the ESR transitions.

3.1. Detection of 2D hydrogen gas by electron spin resonance
Both allowed ESR transitions, $a \rightarrow d$ and $b \rightarrow c$ (fig. 4), can be easily detected during the H\textsubscript{↓} sample accumulation. The ESR lines originating from the bulk gas are broadened due to the inhomogeneity of the polarizing field in the resonator. Soon after switching off the dissociator and cooling the sample cell below 200 mK the $a \rightarrow d$ line disappears indicating that the sample is in the pure $b$ state. A second peak appears on the right (high field) side of the bulk line in the $b \rightarrow c$ spectrum. It is associated with the atoms adsorbed on the cold spot and its shift and strength increase with increasing bulk density and with decreasing temperature of the cold spot. The evolution of the $b \rightarrow c$ transition spectrum recorded during the decay of the H\textsubscript{↓} sample is presented in fig. 6. It has been obtained with the hydraulic valve in sample cell filling line being closed and the temperatures of the mixing chamber, the sample cell and the cold spot coolant being constant. In this conditions the change of the feedback power of the sample cell temperature controller is equal to the recombination power released in the sample cell. By integrating the recombination power we obtain the absolute number of atoms in the sample.
cell. This procedure is used to calibrate the absolute values of the bulk density. To measure the surface density on the cold spot we integrate the absorption spectra of the surface line and compare the integrals with those obtained from the bulk line of the known bulk density.

The separation (shift) between the ESR lines of the bulk and adsorbed atoms is the most easily and accurately measured quantity of the spectra. In fig. 7 we present the shift as a function of the surface density $\sigma$. We carried out measurements for many samples at various temperatures of the sample cell and the cold spot, and found that the shift of the surface line is proportional to the surface density as $\Delta B = 1.0(1) \cdot 10^{-12} \text{[cm}^2\text{G}] \cdot \sigma$. This result is close to the value of the shift calculated for the dipole field of the 2D $\text{H}_{\downarrow}$ atoms but an order of magnitude smaller than the estimated cold collision frequency shift $\Delta B_{ex}$. Our measurement agrees well with the results of the UBC group [14] who observed two ESR side peaks originating from the 2D atoms adsorbed on surfaces having different orientations in the polarizing field. This proves that the effect is anisotropic, giving one more argument for the dipolar origin of the shift. On the basis of our result for the shift and of the observations reported in ref. [14] we conclude that the cold collision shift in 2D $\text{H}_{\downarrow}$ gas is much smaller than the dipolar shift. Recently it has been shown in experiments on RF excitation of $^{87}\text{Rb}$ [23] and $^6\text{Li}$ [24] vapors that the presence of the collisional shift does not depend on the level of coherence in the sample. We anticipate that the absorption of the cold collision shift in 2D hydrogen can be caused by the rapid inelastic process of two-body recombination. Such a process does not occur in the bulk gas because of the need of a third body. On the surface the third body is always present and recombination of unpolarized atoms is very fast. One can estimate that the rate of recombination events $\tau_{rec}^{-1} = l_{bc} v_{th} \sigma$ is comparable to the collisional rate $\tau_{ex}^{-1} = E_{ex}/h$. Here $l_{bc} \approx 0.04[\text{nm/K}] \cdot T$ [25] is the effective recombination cross length, $v_{th}$ is the thermal velocity in 2D gas. A finite lifetime of the $c$ state due to recombination should also broaden the ESR line by the amount of $\Delta B_{rec} \sim \gamma_c \tau_{rec}^{-1} \sim \sigma T^{3/2}$. Indeed the width of the 2D ESR lines observed in our experiments increased with $\sigma$ and surface temperature, in fair agreement with the $\Delta B_{rec}$ given above.

3.2. Surface density and temperature of the 2D gas
Aiming at as high as possible quantum degeneracy of the surface $\text{H}_{\downarrow}$ gas on the cold spot one has to optimize the experimental conditions. The most important parameters in our case are the

![Figure 7. Shift of the ESR absorption line of adsorbed atoms from the bulk line as a function of the surface density. The solid line is a linear fit to the data.](image)

![Figure 8. Density of the bulk gas during decays at the sample cell temperature $T_c = 178\text{ mK}$ and various temperatures $T_m$ of the cold spot coolant.](image)
bulk gas density, the sample cell temperature $T_c$ and the cold spot coolant temperature $T_m$. The rates of the surface recombination and relaxation processes depend exponentially on the surface temperature $T_s$. Therefore, in order to minimize the unwanted recombination and relaxation processes on the sample cell walls, one needs to keep the temperature difference between the sample cell and the cold spot as large as possible. On the other hand, at high enough bulk densities and large $T_c - T_s$ the thermal accommodation heat to the cold spot from the bulk gas becomes a limitation. We found that the optimal cell temperature is in the range $T_c = 150 - 200$ mK, with the cold spot temperature being as low as possible. Such a high temperature of the cell produces a serious heat load to the dilution refrigerator and limits the temperature of the coolant to $\approx 70$ mK. In fig. 8 we present data obtained during several decays at the sample cell temperature $T_c = 178$ mK and various cold spot temperatures. For a high $T_c$ we observe first-order decays governed by $b \rightarrow a$ relaxation on the sample cell walls. The rate constant of this process was minimized to $G_s \approx 8 \times 10^{-2}$ s$^{-1}$ by coating the cell walls with a $\approx 30$ nm thick H$_2$ film. Decreasing the cold spot temperature increases the recombination rate, which is clearly visible from the rate of change of the ESR signal. At the lowest temperature of the coolant the majority of recombination events take place at the cold spot dominating over the sample cell.

The bulk and surface densities are related through the adsorption isotherm (1). In thermal equilibrium, at a constant surface temperature $T_s$ and low quantum degeneracy one expects the linear dependence $\sigma = (T_c/T_s)^{3/2} n \Lambda \exp(E_a/T_s)$ which is confirmed by data at high enough temperatures of the cold spot. In fig. 9 $\sigma$ is plotted as a function of $n$ for various coolant temperatures. The logarithm of the slope of the line $\sigma(n)$ gives ratio $E_a/T_s$. Using the value $E_a = 1.14$ K [25] we calculate the surface temperature $T_s$, which coincides quite well with the highest coolant temperatures $T_m = 128$ mK and $T_m = 142$ mK. For lower coolant temperatures $\sigma$ starts to level off, indicating surface overheating. In this case the temperature of the adsorbed gas can still be extracted from the adsorption isotherm. For high bulk densities "quantum mechanical" isotherms are used, taking into account statistical effects and interatomic interactions as described in sec. 2.1. The results are plotted in fig. 10. Knowing the surface density and temperature we calculate that the maximum 2D quantum degeneracy parameter $\varpi = \sigma \Lambda^2 \approx 1.5$ was achieved in our thermal compression experiments described above.

Figure 9. Surface density on the cold spot as a function of the bulk gas density at $T_c = 154$ mK and various temperatures $T_m$ of the cold spot coolant.

Figure 10. Surface temperature of the H\(_\downarrow\) gas on the cold spot as a function of bulk density at $T_c = 154$ mK and various temperatures $T_m$ of the cold spot coolant.
3.3. Measurement of the three-body recombination rate constant

In order to understand the factors limiting the achievement of higher quantum degeneracy in 2D H↓ we must analyze the main recombination mechanisms leading to the overheating of the surface gas. Three-body dipolar recombination on the surface of the cold spot was expected to be most effective. One may see from the decays in fig. 8 that the contribution of the cold spot to the decay is dominant at the lowest \( T_m \). The total loss rate in the sample cell is calculated from the feedback power of the cell temperature controller. This method is totally independent of the density measurements by ESR. The loss rate has two contributions, one from the cold spot and the other from the rest of the cell walls. To obtain the cell wall contribution we measure the loss rate with the coolant heated to a temperature close to the cell temperature \( T_c \). In such a situation recombination on the cold spot is vanishingly small because of the relatively small spot area. Then, we subtract the background cell contribution from the total rate of recombination events measured for lower temperatures of the coolant, keeping \( T_c \) unchanged.

![Figure 11.](image.png)

Figure 11. Recombination loss rate on the cold spot as a function of the third power of the surface density. Different symbols correspond to various temperatures of the spot coolant.

In fig. 11 we plot the loss rate difference as a function of the third power of the surface density on the cold spot. The linear dependence of the loss rate on \( \sigma^3 \) proves that the recombination process in question is of the third order on surface density, i.e. three-body recombination. The slope of the line in fig. 11 yields the three-body recombination rate constant \( L_s = 2.0(7) \cdot 10^{-25} \text{ cm}^3/\text{s} \). This result is the first direct measurement of \( L_s \) such that both the surface density and the loss rate are obtained by independent methods. It is about an order of magnitude smaller than the values obtained indirectly in earlier experiments [26, 27, 28] where the only measured quantity was the bulk gas pressure or density \( n \). The loss rate was calculated from the time derivative of \( n \), and the surface density was inferred from the adsorption isotherm. Such an approach requires accurate knowledge of the adsorption energy and surface temperature. The latter is not constant during the decay due to the recombination overheating. Our result for \( L_s \) is in fair agreement with the calculations of de Goey [29] and thus settles the long-term discrepancy between theory and experiments.

4. Conclusions

Although we found that the rate of three-body recombination is an order of magnitude lower than expected, yet this process turns out to be the main limitation of the thermal compression method. The heat flux through the surface due to three-body recombination increases rapidly with surface density as \( Q_{\text{rec}} = L_s \sigma^3 f D \), where \( D = 3.7 \times 10^{-19} \text{ J} \) - is the dissociation energy per atom. This heat flux cannot exceed the maximum cooling power of the surface, \( Q_{\text{rp}} = G_{\text{rp}} T_s^{20/3} \).
defined by the thermal contact $G_{rp}$ between the ripplons and phonons of the film\cite{9}. If all other sources of heat to the surface are neglected, we obtain for the maximum value of the quantum degeneracy parameter the relation

$$\varpi_{\text{max}} = \frac{2\pi\hbar^2}{mk_B} \left( \frac{G_{rp}}{DL_s f} \right)^{1/3} T_s^{11/9}. \tag{2}$$

The influence of the quantities $L_s$, $f$ and $G_{rp}$ on the $\varpi_{\text{max}}$ is rather weak, defined by the third-power dependence of the recombination rate on $\sigma$. An estimate of $\varpi_{\text{max}}$ at $T_s = 0.1$ K gives $\varpi_{\text{max}} \approx 1.8$ in good agreement with the values achieved in the experiments. It follows from equation 2 that an increase in the surface temperature may help to reach a higher degeneracy. But in this case the surface density will decrease according to the adsorption isotherm, and one needs to work at much higher bulk densities to keep $\sigma$ the same. This can be done with a more intense source of $\text{H}_\downarrow$ or by compression of the bulk gas. Eventually, another limitation is the growth of the heat flux to the cold spot due to the thermal accommodation of bulk atoms. We estimate that at densities $n = 10^{15} - 10^{16}$ cm$^{-3}$ and surface temperature $T_s \approx 150$ mK one may reach the quantum degeneracy $\varpi \approx 2.5$. Another method would be to increase simultaneously the surface temperature and the adsorption energy $E_a$. The latter can be done by using unsaturated thin films of helium, when the interaction of $\text{H}$ atoms with the strongly attractive solid substrate comes into play.

The quantum degeneracies which can be achieved by the thermal compression method are somewhat lower than the critical value $\varpi = 4$ for the Kosterlitz-Thouless superfluidity transition. They are however larger than unity, meaning that the thermal de Broglie wavelength is larger than the mean interatomic spacing and one may expect that quantum correlations start already to show up. This would influence the interactions in the 2D gas and change the position and shape of the ESR lines of the surface atoms. Another interesting question which calls for further studies is the absence of the cold collision shift of the 2D line. One could study the $a \rightarrow b$ NMR transition of the surface atoms. The scattering lengths of the $a$ and $b$ states are identical, and the cold collision shift should vanish in this case. The dipolar shift depends on the average dipole field in the 2D gas and should remain unchanged. Thus, comparing the shifts of the $a \rightarrow b$ and $b \rightarrow c$ transitions would allow to find the cold collision shift even if it turns out to be small. Because of its low sensitivity NMR cannot be done on the 2D gas in a conventional way. But one may use the calorimetric detection of the transition similar to that used in the magnetic compression experiments\cite{19}. Search for nuclear spin waves in the adsorbed $\text{H}_\downarrow$, already observed in the 3D phase\cite{30}, would be also of great interest.

The thermal compression method is well suited for the studies of the equation of state of the 2D $\text{H}_\downarrow$ gas. In the experiments described here the dense bulk gas above the surface defines the chemical potential in the system and the surface density of the adsorbed gas. One may consider the opposite case, in which most of the sample is adsorbed on the surface without almost any atoms in the bulk. This situation can be realized at somewhat lower temperatures of the walls, $T_s \lesssim 50$ mK. Having a spot on the wall at a different temperature but in a dynamic equilibrium with the rest of the cell will imply that the 2D pressure $p_s$ remains constant along the surface. Then, the ratio of density on the spot to that on the cell walls would give a possibility to check the equation of state $p_s(T_s)$ in the 2D gas. One can estimate, that the exchange interaction energy $E_{ex} \approx 25$ mK at $\sigma = 5 \times 10^{12}$ cm$^{-2}$ becomes comparable with the temperature of the surface gas. Therefore, deviations from the ideal gas law $p_s = \sigma k_B T_s$ should be quite easily observed. To our knowledge, this would be the first measurement of the equation of state of a two-dimensional quantum degenerate gas.
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