Electron-spin resonance in quantum degenerate 2D atomic hydrogen gas

Sergey Vasilyev [a,1], Jarno Järvinen [a], Alexandr Safonov [b], Simo Jaakkola [a]

[a] *Department of Physics, University of Turku, FIN-20014 Turku, Finland*

[b] *ISSSP, RRC Kurchatov Institute, 123182 Moscow, Russia*

Abstract

We report on experiments where two-dimensional Bose gas of atomic hydrogen has been compressed thermally on the surface of a small cold spot covered with superfluid helium ^{4}He at temperatures below 100 mK. The maximum achieved surface densities, up to $\sigma \approx 5 \times 10^{12}$ cm^2, are well inside the quantum degeneracy regime with $\sigma\Lambda^2 \approx 1.7$. Detection of the adsorbed H↓ atoms *in situ* by ESR yields direct information on the surface density and temperature profiles across the cold spot and on the mean dipolar field and interatomic interactions in the 2D gas.

Key words: two-dimensional Bose gas; atomic hydrogen; superfluidity

Spin-polarized hydrogen H↓ adsorbed on the surface of superfluid helium is a unique 2D Bose gas, which is expected to exhibit collective quantum phenomena such as Berezinskii-Kosterlitz-Thouless transition or quasicondensate formation at experimentally accessible temperatures $T_S \approx 100$ mK and surface densities $\sigma \approx 10^{13}$ cm^{-2}. Magnetic compression has proven to be an effective tool to get into the quantum degeneracy regime [1]. However, the strong inhomogeneities of the field required for magnetic compression method render the use of magnetic resonance impossible for direct detection of the adsorbed gas. In the present work we have chosen the method of compressing H↓ thermally on a miniature "cold spot" (CS) at the sample cell wall [2],[3]. In this case high resolution electron spin resonance (ESR) may be employed for *in situ* diagnosis of the 2D sample and its interatomic interactions. It is found that the ESR line of the adsorbed atoms is shifted from that of the bulk gas due to internal dipolar field in the 2D system. The shape and position of the 2D line appears to be strongly dependent on the value of excitation microwave field [4]. ESR instability effects due to ESR- induced recombination may lead to peculiar saw-tooth lineshapes [4] observed also by Hardy and coworkers in [5].

Hydrogen atoms are produced in a low-temperature dissociator and accumulated into a 40 cm^3 buffer volume connected by a short tube to a 1.5 cm^3 sample cell (SC). All three volumes (fig. 1) are linked to a different stages of dilution refrigerator, and their temperatures are separately controlled. Presence of large buffer reservoir kept at a relatively high temperature of $T_B = 350$ mK ensures a long, exceeding 1 h decay time of the H↓ sample even at SC temperatures $T_{SC} \approx$ 100 mK. The cell contains a semiconfocal Fabry-Perot resonator with a "cold spot" in the middle of its flat mirror. The spot is thermally isolated from the cell by a 0.5 mm thick Stycast 1266 disk covered with a 12 μm thick gold-coated Kapton foil. There is a 1.5 mm diameter hole in the Stycast disk through which the foil is flushed from beneath by the cold ^{3}He-^{4}He mixture of a dilution refrigerator stabilized within a range $T_C = 40...150$ mK. This provides an effective cooling of the spot which can be rapidly "switched on and off" by the heat supplied to the incoming coolant. All inner surfaces of the SC are lined with a film of isotopically purified ^{4}He.

Since ESR-induced recombination was found to be

[1] Corresponding author. E-mail: servas@utu.fi

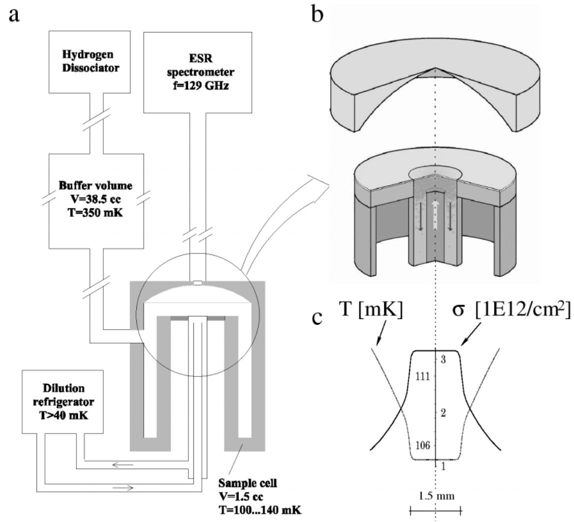

Fig. 1. Schematic drawing of (a) the cryogenic part of the experimental setup, (b) ESR resonator with the "cold spot" and (c) calculated temperature and density profiles over the cold spot.

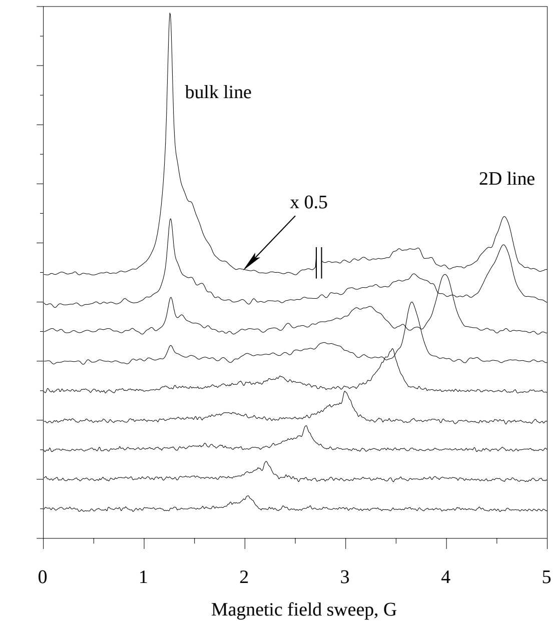

Fig. 2. ESR spectra recorded during a decay of H↓ sample at $T_{SC} = 102$ mK, $T_B = 350$ mK, $T_C = 50$ mK. The traces are recorded during a 100 s sweep each with 500 s time intervals.

responsible for the above-mentioned instability effects and distorted lineshapes [4], we kept here the microwave excitation power low enough, below 0.1 nW. A cryogenic heterodyne ESR spectrometer operating at 129 GHz and capable of detecting 10^9 atoms was used for the diagnostics of H↓.

In a typical experiment atomic hydrogen is accumulated in the buffer volume and the SC up to the densities 10^{15} cm^{-3}. At this stage the ESR spectra (fig.2) contain an inhomogeneously broadened bulk line only. Soon after switching off the dissociator the SC and the buffer volume cool down to the desired temperatures, hydrogen in the cell becomes doubly polarized, its bulk density decays to about 2×10^{14} cm^{-3} and a 2D line appears in the ESR spectrum whose evolution is recorded during the sample decay. The 2D signal is shifted to higher magnetic fields with respect to the corresponding bulk line due to the average dipolar field proportional to the 2D density σ. We found the shift $\Delta h_d = 1.0(1) \times 10^{-12}$ G×cm$^2 \times \sigma$ in good agreement with a theoretical value [6]. The areas under the bulk and surface ESR absorption curves are proportional to the respective densities n and σ. The absolute density values were calibrated calorimetrically integrating the heat liberated in the SC due to recombination of the sample. Equilibrium surface density is related to the bulk density according to the adsorption isotherm, which gives an estimate of the temperature T_S of adsorbed H↓.

A non-uniform temperature profile around CS implies an inhomogeneous surface density profile $\sigma(r)$. The density gradients create a 2D hydrodynamic flow of hydrogen on the CS which is damped by ripplons and by the exchange of atoms with the bulk gas. Numerous recombination mechanisms are responsible for overheating the surface gas above the temperature of the substrate. We have developed a numerical model to calculate the evolution of temperature and density profiles across the CS (fig. 1 c) and the simulated density distributions result in ESR lineshapes close to those observed in experiments (fig.2). The maximum achieved surface densities are $\sigma \approx 5{\times}10^{12}$ cm^2 at $T_S \approx$100 mK corresponding to the quantum degeneracy parameter $\sigma\Lambda^2 \approx 1.7$. At present we are limited by the above-mentioned 2D flow and recombination heating of H↓.

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References

[1] A.I. Safonov *et al.*, Phys. Rev. Lett. **81** (1991) 4545.

[2] B.V. Svistunov *et al.*, Phys. Rev. B **43** (1991) 13412.

[3] A. Matsubara *et al.*, Physica B **194-196** (1994) 899.

[4] S. Vasilyev *et al.*, to be published.

[5] I. Shinkoda and W.N. Hardy, J. Low Temp. Phys. **85** (1991) 99.

[6] B.J. Verhaar, ref. 13 in [5].

[7] A.I. Safonov *et al.*, Phys. Rev. Lett. **86** (2001) 3356.