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Apparatus for Optical Study of Atomic Hydrogen on the Surface of Liquid Helium

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Spin-polarized atomic hydrogen adsorbed on the surface of liquid helium is the most promising candidate for the observation of quantum degeneracy in a two-dimensional Bose gas. In this article we describe our experimental apparatus which is being used to realize this goal. The apparatus employs a system of superconducting and iron magnets to supply electron and proton spin-polarized hydrogen to a cold cell ($T \approx 0.1\,\mathrm{K}$) at sufficient flux to compensate recombination losses and attain the regime of two-dimensional quantum degeneracy. The gas in the cell is probed using light resonant with the Lyman-α atomic transition.

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1. INTRODUCTION

Atomic hydrogen (H) adsorbed on the surface of liquid helium is the best example in nature of the fundamentally important two-dimensional Bose gas.[1] Present experimental efforts are concentrated on attaining the conditions for quantum degeneracy.[2] Important questions concern the Kosterlitz-Thouless (KT) transition in a Bose gas and its relation to Bose-Einstein condensation, and the role of interactions and confining potentials.

From theoretical study of the weakly interacting 2-d Bose gas the following picture has emerged. At zero temperature, the gas is Bose condensed. At non-zero temperature thermally excited phonons wash out long-range phase coherence, turning the condensate into a "quasicondensate" (conden-

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sate with fluctuating phase). Still, the gas is superfluid and local coherence properties are those of a gas with a condensate. At a critical temperature T_{KT} superfluidity is destroyed by the Kosterlitz-Thouless vortex mechanism. The fate of the quasicondensate is not clear – it may persist to somewhat higher temperature or vanish at the transition like the condensate in a 3-d Bose gas. In any case, well above T_{KT} the gas will be "normal".

No experiment under development aims to observe superfluidity of H. Instead the goal is to observe the quasicondensate through its influence on the equation of state of the gas and on inelastic processes. In normal gas the atoms are bunched like photons in chaotic light. In the quasicondensate they are not. As a result, deep in the superfluid phase the energy of the gas resulting from elastic interatomic interaction is reduced by a factor of two and three-body recombination is reduced by a factor of six compared with the normal phase.[3] That the atoms collide not in vacuum but in a medium (the H gas itself) may make these factors even larger.[4]

The recombination of atomic hydrogen to form molecular hydrogen is a central issue in experiment design. Modern experiments rely on an "open geometry" – a high density of H is attained only locally while recombination heating is distributed globally by allowing recombined hydrogen molecules to disperse before releasing their vibrational energy. Restricting the size of the dense part of the H sample is also important to limit the total recombination heat load on the dilution refrigerator and to allow for continuous replacement of H atoms lost by recombination. The magnetic compression technique pioneered by the Turku/Moscow collaboration has brought atomic hydrogen to the onset of two-dimensional degeneracy.[5] Variations of this method form the basis of experiments at Harvard[6] and in Amsterdam. A nonmagnetic technique, the "cold spot", is being used in Kyoto.[7]

In this paper we describe the experimental apparatus that we are using in Amsterdam to attain and study quantum degeneracy in two-dimensional atomic hydrogen.

2. APPARATUS

The heart of the experimental setup (Fig. 1) resides in the bore of a superconducting solenoid and provides an environment (magnetic field of several tesla, temperature below 1 K, and a superfluid helium film covering all surfaces) in which spin-polarized atomic hydrogen is especially stable. There are two volumes, the "buffer" and the "cell", which are thermally isolated from each other. In the tube connecting these volumes a dip in the magnetic field strength produces a potential energy barrier for H atoms. This permits the buffer to act as a source of doubly (electron and proton

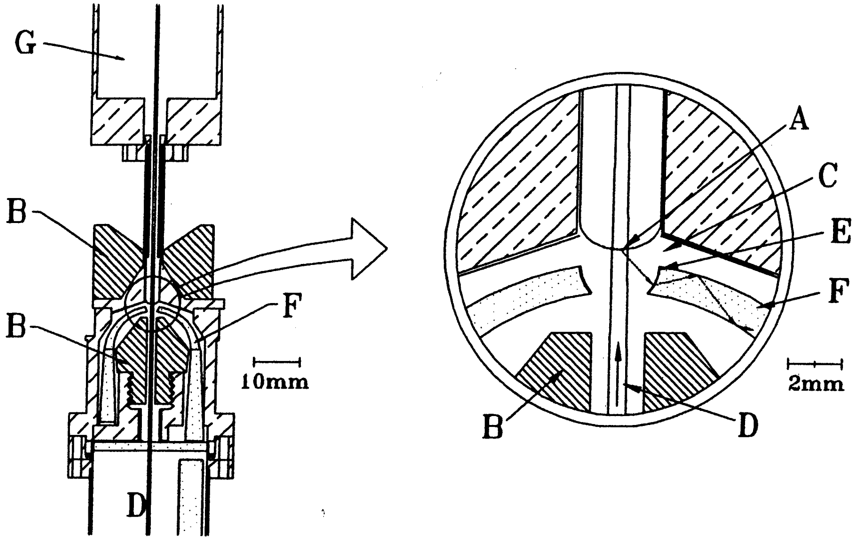


Fig. 1. Experimental setup. A - Helium meniscus and 2-d H gas; B - CoFe magnets; C - Liquid helium (0.1 K); D - Lyman-α probe beam; E - Phosphor; F - Light guide for fluorescence detection; G - Buffer volume (0.25 – 0.4 K).

spin) polarized H to be fed into the cell in which the gas is compressed to degeneracy.

In the experiment the buffer is filled with electron spin-polarized hydrogen from a cryogenic dissociator. At 0.25 K the magnetic potential barrier prevents the atoms from reaching the cell. While stored in the buffer, the gas becomes proton spin-polarized by recombination. The buffer is then warmed to cause H to flux into the lower part of the apparatus, which is nearly filled with liquid helium leaving only a test-tube shaped free volume (the cell) for the H gas. The liquid helium is cooled to 0.1 K, resulting in strong adsorption of H to form a 2-d gas whose density increases until the flux into the cell is balanced by three-body recombination on the surface. Varying the temperature of the buffer varies the flux to scan the 2-d H density across the KT transition.

The magnetic field profile in the apparatus (Fig. 2) is shaped by two CoFe[8] pieces axially magnetized to saturation by the high field of the solenoid. The shape of each magnet is a polygon revolved about the z-axis. From a polygon side extending from cylindrical coordinates $(\rho, z) = (a_1, z_1)$ to (a_2, z_2) the field B on the axis at z is given by

$$\frac{2B}{\mu_0 M} = \frac{1}{s^2}\left(\frac{\tilde{z}_1}{r_1} - \frac{\tilde{z}_2}{r_2}\right) + \frac{t}{s^2}\left(\frac{a_2}{r_2} - \frac{a_1}{r_1}\right) + \frac{t^2}{s}\ln\left(\frac{\tilde{z}_1 + r_1 s + 2a_1 t}{\tilde{z}_2 + r_2 s + 2a_2 t}\right) \tag{1}$$

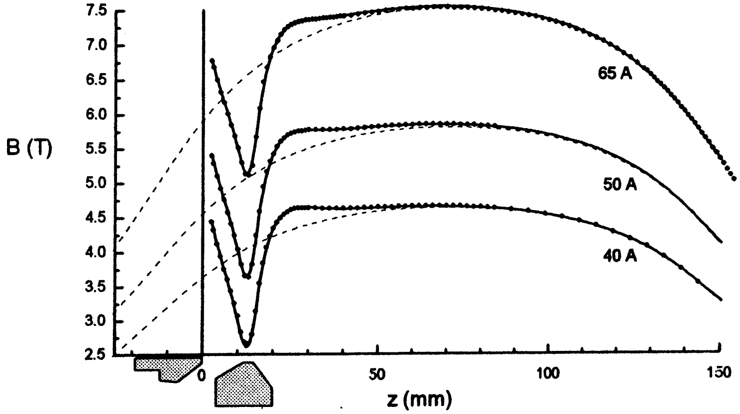
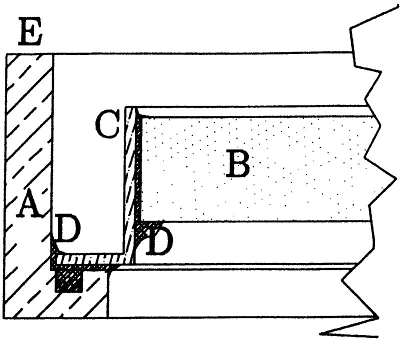


Fig. 2. Magnetic field profile along z axis for several solenoid currents: dots - measured; dashed - calculated solenoid field; solid - calculated total field. Shaded polygons indicate CoFe magnet shapes and positions. The helium meniscus is at $z = 2\,\mathrm{mm}$, the solenoid center is at $z = 72\,\mathrm{mm}$.

where M is the magnetization ($\mu_0 M = 2.35\,\mathrm{T}$), $\tilde{z}_i = z_i - z$, $r_i = (\tilde{z}_i^2 + a_i^2)^{1/2}$, $t = (a_2 - a_1)/(\tilde{z}_2 - \tilde{z}_1)$, and $s = t(1 + t^{-2})^{1/2}$.

In the cell the strong magnetic field gradient ($B' = -168\,\mathrm{T/m}$) compresses the H so that the highest density occurs at the center of the helium meniscus. At 0.1 K the KT phase transition occurs at a 2-d gas density $n_2 = 10^{13}\,\mathrm{cm}^{-2}$. This estimate follows from the universal critical relation $n_2^s \Lambda^2 = 4$ where n_2^s is the superfluid density and $\Lambda = (2\pi\hbar^2/mkT)^{1/2}$ is the thermal de Broglie wavelength of an H atom; interactions in H are strong enough that n_2^s is approximately equal to n_2 at the transition. The 3-d gas, whose density is $n_3 = 10^{15}\,\mathrm{cm}^{-3}$ just above the surface, forms an atmosphere 1 mm thick through which excited molecules formed by recombination easily pass to distribute their energy over the cell and buffer. Total recombination heating is about $50\,\mu\mathrm{W}$. An atom injected into the cell recombines in 100 ms; the continuous flux of atoms from the buffer extends the measuring time to 100 s. The gas in the cell is in thermal equilibrium (the thermalization time is 2 ms) and the atoms recombine instead of returning to the buffer (the escape time is about 2 s).

The H gas in the cell (the 2-d gas on the surface and the 3-d gas above it) is interrogated using resonant spectroscopy on the Lyman-α transition (wavelength 122 nm), a method we have used previously for studies of magnetically trapped H.[9] Because of the large number of atoms in the optical path, spectroscopy on resonance (e.g., for Zeeman thermometry of the 3-d gas above the surface) is best done on the $1^2S_{1/2}, m_j{=}-1/2$ to $2^2P_{3/2}, m_j{=}1/2$ transition, which has a sufficiently small cross section in the



A : Stainless steel flange
B : Single crystal MgF_2 window, diameter 25 mm, thickness 2 mm
C : Machined Vespel SP-1 strain relief ring, thickness 0.2 mm
D : Filled epoxy (Stycast 2850)
E : Indium sealing surface

Fig. 3. Cross section of the low temperature MgF_2 window flange.

strong magnetic field to avoid problems with optical thickness.

The possibility of fluorescence detection of adsorbed H atoms was analyzed by Svistunov *et al.*[10] The $1S$-$2P$ optical transition is broadened by interaction of the $2P$ atom with the liquid helium. By detuning far to the blue of the natural resonance, the 2-d H density may be determined without interference from H-H interactions or from the 3-d gas.

The Lyman-α light beam enters the cell from below through a single-crystal MgF_2 window cut with its optic axis parallel to the beam. Our usual technique of sealing small windows directly with indium o-rings was not reliable with the large (25 mm clear diameter) window needed here. Hence, we developed a more reliable window flange (Fig. 3) in which the window is epoxied (Stycast 2850GT/24LV) into a Vespel SP-1 strain relief ring which is epoxied to the stainless steel flange.[11]

Photons scattered by H atoms are downconverted to visible light by a phosphor (TPB) and guided to a photomultiplier at room temperature. This fluorescence signal is proportional to the 2-d H density.[10] The beam passing through the cryostat is detected by a second photomultiplier, allowing transmission measurement of density and temperature of the 3-d gas. Together, this information will enable reliable determination of the equation of state of the 2-d gas and facilitate study of correlation-induced changes in the rate of three-body recombination.

3. CONCLUSION

The apparatus described here is now being used to investigate quantum degeneracy in 2-d H. The first measurements of the optical spectrum of H adsorbed on liquid helium are also being made. In addition, prospects exist for photoassociation spectroscopy of dense 3-d H as well as study of quantum correlations in radiative atomic collisions.

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