Magnetic compression of two-dimensional spin-polarized atomic hydrogen

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We have compressed spin-polarized atomic hydrogen adsorbed on the surface of liquid ^{4}He in a strongly nonuniform magnetic field to the onset of Berezinsky–Kosterlitz–Thouless phase transition. A method is introduced to detect adsorbed H atoms by measuring the lifetime of a small artificial impurity of reactive a-state atoms in the otherwise doubly polarized (b-stage) hydrogen sample. © *1995 American Institute of Physics.*

1. Compression of a small portion of the sample into the potential well formed by locally enhanced field was proposed by Kagan and Shlyapnikov[1] as a method to achieve Bose–Einstein condensation in spin-polarized atomic hydrogen ($H\downarrow$) gas. We have utilized this idea here to compress hydrogen atoms adsorbed on the surface of liquid helium for the purpose of achieving a Berezinsky–Kosterlitz–Thouless (BKT) transition to the state of two-dimensional superfluidity. This transition is expected to occur when the following condition is satisfied:[2]

$$\sigma_s\lambda_{th}^2=4; \quad \lambda_{th}^2=\frac{2\pi\hbar^2}{mT}. \tag{1}$$

Here σ_s is the density of the superfluid component of the two-dimensional gas which is close to its total density σ, and λ_{th} is the thermal de Broglie wavelength, where m is the atom, mass, and T is the temperature of the gas. At the transition σ should increase by a factor of almost 2 to the value defined by Eq. (1) (Ref. 3), while the constant K_{bbb} of a three-body dipole recombination, which determines the decay of the sample, should exhibit a sixfold decrease.[4,5] Therefore, the change in the total loss rate of the atoms, $L\propto K_{bbb}\sigma^3$, is probably too small to be detected reliably in an experiment. Hence, it may turn out to be necessary to monitor not only L but also σ.

In our experiments we compressed magnetically a two-dimensional atomic hydrogen in high-field seeking states $H\downarrow$ to a high density in a potential well formed by a miniature dysprosium field intensifier on its superfluid ^{4}He film-covered pole face. The surface density of hydrogen atoms was determined by a novel method based on a pulsed excitation of a nuclear transition $b\rightarrow a$ with a subsequent detection of heat released in an exchange recombination induced accordingly.

2. The sample cell of volume $V=4$ cm^3 and inner surface area $A=20$ cm^2, shown schematically in Fig. 1, was located at the center of a superconductive solenoid in a field $B_0=4.57$ T. To measure and stabilize the cell temperature, $T_{\text{cell}}=100$–200 mK, we used

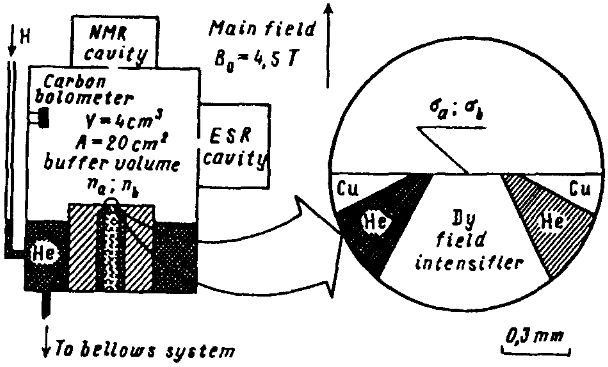

FIG. 1. Schematic diagram of the sample cell. The inset shows the design of the "magnetic spot."

two thick-film thermometers. One thermometer, made of colloidal carbon (Aquadag)[6] and immersed in bulk liquid helium inside the cell, was employed to stabilize T_{cell} within ± 5 μK. The other, a RuO_2-based chip resistor attached to the outer cell wall, was calibrated against a ^{3}He melting-curve thermometer and SRM 768 superconductive fixed-point device. It provided an absolute accuracy better than 1 mK for T_{cell}. Hydrogen atoms were introduced into the cell from a low-temperature dissociator.

In our temperature range a preferential recombination of atoms in the mixed state, $|a\rangle=|\downarrow\Uparrow\rangle-\varepsilon|\uparrow\Downarrow\rangle$, quickly lead to the formation of a doubly polarized (by electron and nuclear spins) hydrogen sample, which consists mainly of atoms in the pure state $|b\rangle=|\downarrow\Downarrow\rangle$ [here $\varepsilon\approx A_s/4\mu B$ is a mixing parameter, where A_s is the hyperfine constant. The arrows $\downarrow(\uparrow)$ and $\Downarrow(\Uparrow)$ designate projections of, respectively, electron and nuclear spins onto the direction of the magnetic field B]. To obtain a higher nuclear polarization i.e., higher value of the ratio n_b/n_a of bulk densities in the large low-density "buffer" volume, we coated the cell walls with a layer of solid H_2 in order to substantially suppress the nuclear relaxation $b\rightarrow a$ due to magnetic impurities in the bulk of the cell. The densities n_a and n_b $(n=n_a+n_b)$ were measured with an accuracy of 5×10^{11} cm^{-3} by a homodyne ESR spectrometer.[6]

We measured the total loss rate of hydrogen atoms in the cell using an Aquadag bolometer.[6] We used it because only about 1% of the recombination energy, $D=4.6$ eV (per molecule), is released locally into the helium film at the site of the reaction.[7] The main part of D is carried away by highly excited H_2 molecules and then distributed uniformly along the cell surface, including the bolometer. The bolometer temperature, T_{bolo}, is determined by a recombination and bias heating of the bolometer and by its thermal coupling with the cell body at T_{cell}. The latter consists of a thermal accommodation of hydrogen atoms at the bolometer surface and of a heat conductivity of ripplons on the helium film that covers the leads. The thermal coupling and the bias current were chosen in such a way that the change in the bolometer resistance would be linear in the heating power over the whole range of the measured recombination rates.

The H$\downarrow$ gas was adsorbed to a high surface density at a small spot on the ^{4}He film-covered, 300-μm-diam. pole face of the Dy field intensifier (shown in Fig. 1). The

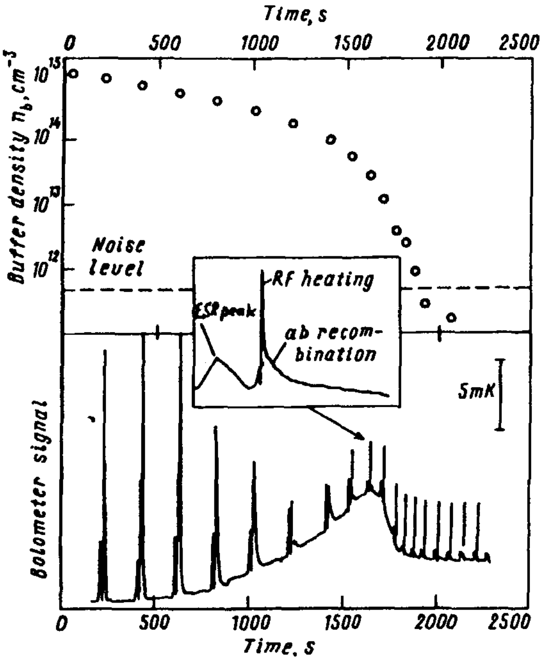

FIG. 2. Data recorded by ESR and bolometer in a density decay experiment at $T_{cell}=160$ mK with the magnetic spot "open."

intensifier tip provided a nearly rectangular distribution of the additional magnetic field, ΔB, along the pole face. By raising (lowering) the helium level in the cell with the help of a bellows system we were able to shut off (open) the region of maximum field and thus stop (activate) the magnetic compression. In the same way we closed (opened) the H filling line. A capacitive gauge was employed to measure the helium level height with a precision of a few microns. In order to avoid ambiguity in the adsorption energy E_a of H atoms we carried out a heat flush and superleak purification of the ^{4}He used in the cell with respect to ^{3}He impurity.

Application of short (1–30 ms) microwave pulses to a cavity resonant at 910 MHz, which was attached to the sample cell, converted a small (up to 4%) portion of the b-state sample into the a state. The additional exchange recombination $a+b \rightarrow H_2$, induced by NMR, caused a pronounced peak of the bolometer signal. The relaxation time of the signal back to its original level is the lifetime τ of the additional a atoms, which are directly related to the surface density of b atoms, σ_b, at the place where the a-b exchange recombination occurs.[8]

Figure 2 shows data recorded in a typical experiment at $T_{cell}=160$ mK. The upper part of the figure shows the decay of the buffer volume density n_b of the b atoms measured by ESR when the magnetic spot was "open." In this experiment n_a was below the noise level of the spectrometer. Corresponding variation of the bolometer temperature is shown in the lower part of the figure. Pairs of peaks are seen at the bolometer signal.

The first peak of each pair (see the inset) results from a recombination of atoms in the upper hyperfine state, $|c\rangle=|\uparrow\Downarrow\rangle, +\varepsilon\downarrow\Uparrow\rangle$ formed when the magnetic field is swept through the $b\rightarrow c$ resonance[6] to measure n_b by ESR. After sampling the bulk density we applied a short resonant pulse to the NMR cavity in order to flip the nuclear spins of a small portion of the b atoms. We see in the insert a corresponding short rf heating pulse followed by a much longer tail caused by an exchange recombination of additional a atoms produced in this manner. During the presence of the tail n_b remains nearly constant and so does the response of the bolometer. Hence the change of its temperature is proportional to the total loss rate of atoms in the cell. As explained below, a set of observed decay time constants of the tails τ (actually, the lifetimes of the additional a atoms) versus the bulk density n_b is used to determine the surface density σ_b of the atoms adsorbed at the magnetic spot.

3. We studied the dependence of τ on n_b at different cell temperatures with the spot open and closed. For the closed spot we have $\tau^{-1}=K_{ab}^{\text{eff}}n_b$, where the effective rate constant is[9]

$$K_{ab}^{\text{eff}}=\frac{A}{V}\,\lambda_{th}K_{ab}(B_0)\exp\left(\frac{2E_a}{T_{\text{cell}}}\right); \quad K_{ab}\sim\frac{\sqrt{T}}{B^2}. \tag{2}$$

The observed temperature dependence of K_{ab}^{eff} yields $E_a=1.03(3)$ K for the adsorption energy of hydrogen on ^{4}He and $K_{ab}=1.9(5)\times10^{-9}\ \text{cm}^2\cdot\text{s}^{-1}\cdot K^{-1/2}$ for the intrinsic exchange recombination rate constant at $B_0=4.57$ T, in agreement with the values obtained earlier.[9] Our result for K_{ab} is the first direct result which is not affected by other processes such as aa recombination and nuclear $b\rightarrow a$ relaxation.

Figure 3 shows τ plotted as a function of n_b at three different cell temperatures. For low densities the recombination even at the magnetic spot is slow and consequently heat generation is small. The temperature of the spot, T_{spot} is therefore almost equal to T_{cell} and again τ^{-1} is directly proportional to n_b. In the low-n_b limit the contribution of the spot to τ^{-1} as separated from that of the rest of the cell surface, $(\tau^{-1})_{\text{spot}}=\tau^{-1}-(\tau^{-1})_{\text{cell}}$ is

$$\left(\frac{1}{\tau}\right)_{\text{spot}}=\frac{A_{\text{spot}}}{V}\,\lambda_{th}K_{ab}(B_0+\Delta B)\exp\left(\frac{2E_a+2\mu\Delta B}{T_{\text{cell}}}\right)n_b, \tag{3}$$

where $A_{\text{spot}}=7\times10^{-4}$ cm^2 is the area of the spot. From the temperature dependence of the prefactor of n_b in Eq. (3) we obtain $\Delta B=2.11(1)\ T$ for the field enhancement at the spot. With growing n_b, the recombination rate at the spot increases and leads to overheating. This can be seen as a deviation of the τ-vs-n_b curves from the inverse proportionality. Further increase of T_{spot} with increasing buffer volume density makes the spot "invisible," since most of the additional a atoms recombine on the colder cell walls. In this case τ approaches its "closed-spot" value.

Once τ-vs-n_b curves have been measured, we can determine the surface density of the b atoms at the spot, even if its temperature due to the overheating differs from that of the cell, because

$$\left(\frac{1}{\tau}\right)_{\text{spot}}=\frac{A_{\text{spot}}}{V}\,K_{ab}\sigma_b\,\frac{\sigma_a}{n_a}, \tag{4}$$

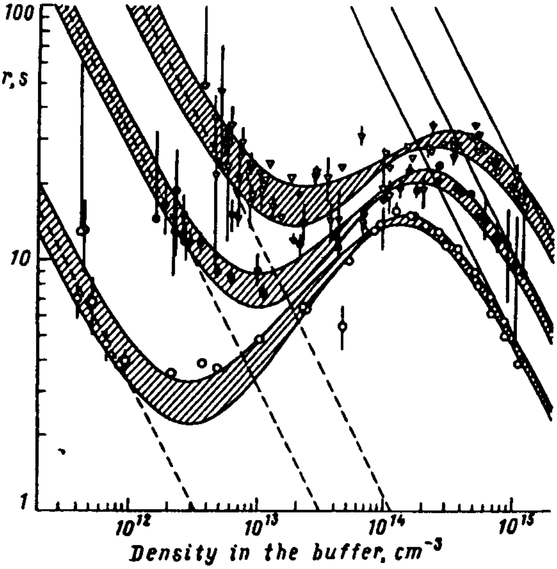

FIG. 3. Dependence of the lifetime of the NMR-induced a atoms on n_b for the "open" spot at $T_{\rm cell}=160$ mK (open circles), 170 mK (closed circles), and 180 mK (triangles). Solid lines represent the "closed" spot and dashed lines correspond to the spot which is not overheated in the case of an ideal Boltzman gas. The bands result from a fit to a semiempirical equation which is strictly valid in both high- and low-n_b limits.

where $K_{ab}=K_{ab}(B_0+\Delta B)$ and in the classical limit $\sigma_a/n_a=\sigma_b/n_b$. The values of the surface density calculated in this way are shown in Fig. 4 (curves *1*). We see that at high buffer volume densities n_b the magnetically compressed, two-dimensional gas approaches degeneracy: $\sigma_b\lambda_{th}^2\sim 1$. We should therefore use an adsorption isotherm which takes into account the Bose statistics and the mutual interaction of hydrogen atoms. Relations introduced by Svistunov *et al.*[3] lead to a set of equations for σ_b and the spot temperature $T_{\rm spot}$:

$$\left(\frac{1}{\tau}\right)_{\rm spot}=\frac{A_{\rm spot}}{Vn_b}K_{ab}\sigma_b\lambda_{th}^{-2}(1-e^{-\sigma_b\lambda_{th}^2}), \tag{5}$$

$$T_{\rm spot}=(E_a+\mu\Delta B-2U\sigma_b)\ln^{-1}\left(\frac{1-e^{-\sigma_b\lambda_{th}^2}}{n_b\lambda_{th}^3}\right), \tag{6}$$

where $U=5\times 10^{-15}$ K·cm^2 is an effective mean-field parameter of the interaction of the adsorbed hydrogen atoms. A numerical solution of this set of equations for experimental data of τ and n_b and measured E_a and ΔB is also shown in Fig. 4 (curves *2*). Note that the maximum surface density attained in the present experiments is $\sigma_b=2.2(5)\times 10^{13}$ cm^{-2} at the temperature of the two-dimensional gas, $T_{\rm spot}=225(7)$ mK. It corresponds to the value of the quantum degeneracy parameter $\sigma_b\lambda_{th}^2\approx 2$ at the onset of the BKT phase transition.

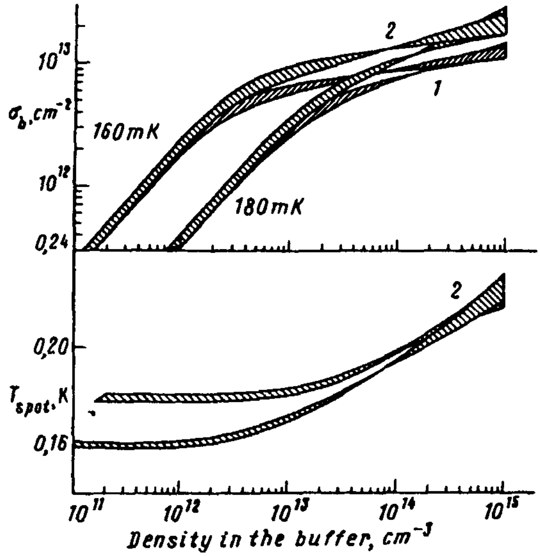

FIG. 4. Bulk density variation of the density and temperature of a magnetically compressed H↓ overlayer for two values of T_{cell}. The width of the bands corresponds to the experimental scatter in τ.

When the surface density has been determined, we can also find the rate constant of the three-body dipole recombination: $K_{bbb}=L/(A_{\text{spot}}\sigma^3)$, because the total recombination rate L is measured by the bolometer and ESR. We obtain the value $K_{bbb}=1.9(5)\times 10^{-24}$ cm$^4\cdot$s^{-1}, which is essentially constant over the whole density range covered here. This proves the assumption that the dipole recombination at the spot determines the sample decay. Our result for K_{bbb} is in agreement with the theoretical results[4,5] and with the earlier experimental results.[10]

In our approach we implicitly assumed an allowance to the average density and temperature of the two-dimensional gas over the magnetic spot area. It is based on nearly rectangular profile of the additional magnetic field and proved by measurements of the rate constants and by the results of a numerical simulation of the heat balance at the spot.[8] It should be pointed out that a dynamic equilibrium in the sample is determined by the rate of the particle exchange between the 2D gas at the spot and the 3D phase in the low-density buffer volume. This rate is more than two orders of magnitude higher than the recombination loss rate of atoms.

4. In conclusion we would like to emphasize that in the present experiment all the quantities needed to determine the surface density σ_b of hydrogen, i.e., the adsorption energy E_a, the rate constants K_{ab} and K_{bbb}, and the magnetic field enhancement ΔB, were measured simultaneously. The record value of σ_b obtained here is limited by the recombination overheating of the compression region. Since the removal of heat from the magnetic spot is controlled by the thermal conductivity of ripplons on the liquid helium film, a further increase of the surface density apparently can be achieved by reducing the characteristic size of the spot.

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