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Published in:
Physical Review. B, Condensed Matter

DOI:
10.1103/PhysRevB.25.6002

Ballistic heat pulses in spin-polarized atomic hydrogen to $T=200$ mK

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(Received 31 December 1981)

We have used a heater and bolometer to create and detect ballistic heat pulses of spin-polarized hydrogen atoms (H↓). Energy can be effectively coupled from helium-covered walls to the H↓ gas without recombination. The energy-loss coefficient of H↓ on ^{4}He has been measured to be 0.2 ± 0.1. This technique can be considered as the generation of very-low-velocity atomic beams of H↓, down to 200 mK.

Since atomic hydrogen was stabilized[1] as a spin-polarized gas (H↓), a number of experiments have been carried out to measure its quasiequilibrium properties. In this paper we present new experimental results in which we generate ballistic heat pulses. We have been able to couple energy into a gas of H↓ through helium-covered walls in a hydrogen stabilization cell (HSC), creating a ballistic heat pulse of hydrogen atoms. The pulse is detected by coupling energy back into a helium-covered bolometer. These pulses have been studied as a function of ambient temperature (200–500 mK) by measurement of the time-of-flight spectrum (TOF), all in the low-density ballistic regime. Our measurements provide the first determination of the energy-loss coefficient for H atoms scattering off of a He surface. A fit to theoretical TOF curves indirectly implies that the Kapitza resistance of thin He films is anomalously larger than for bulk helium. Our techniques are easily extended into the high-density viscous regime for generating sound waves and possibly may be applied to study propagation of H↓ on surfaces of helium as a two-dimensional gas. Finally we note that a ballistic pulse can be considered as an atomic beam of spin-polarized hydrogen at temperatures as low as 200 mK with fluxes of $10^{17}-10^{18}$ atom/cm^2 sec.

H↓ was loaded into the HSC from a room-temperature discharge by techniques described elsewhere.[1]. The HSC, shown in Fig. 1, was centered in the bore of a superconducting solenoid operated nominally at 8 tesla. The cell was cooled by a copper rod connected to the mixing chamber of a dilution refrigerator, enabling a temperature range from about 30 mK to several hundred mK. The surfaces of the HSC were covered with undersaturated films of either ^{4}He or ^{3}He-^{4}He mixtures estimated to be about 150-Å thick. We stress that if any surface is instantaneously bare of He, the H↓ will condense and rapidly recombine. This, in fact, is the principle of the "trigger" bolometer detector used to determine the density[1]: A resistive element is heated with an electrical current pulse sufficiently long to desorb the helium, with a resultant rapid recombination of the H↓ and heating of the cell due to the liberated recombination energy. Such a trigger bolometer was incorporated in our cell. The loading of the cell with H↓ was straightforward,[1] although an as yet unidentified problem has reduced our filling flux orders of magnitude down to less than 10^{12} H↓/sec so that to reach densities of order 10^{15}/cm^3 required an hour or two and restricted these measurements to low density.

The objective of the current work was to extend the study of H↓ to translational dynamics of the

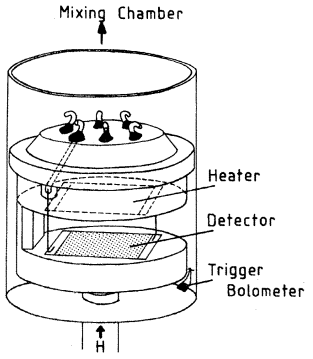

FIG. 1. HSC design.

gas. After also considering the use of microphones and torsional oscillators we came to the conclusion that the most effective way to disturb the equilibrium of the gas might be with pulsed heaters using bolometer detectors, which of course must not induce recombination in the gas of H↓. Such techniques have been used to study He films[2] where a heat pulse evaporates a group of He atoms which propagate to the detector and adsorb with a sticking coefficient of ~ 1. The situation in our case is quite different. Coverages of H↓ on the He are of order $10^9/\text{cm}^2$ and their evaporation gives a negligible contribution to the signal. The group of disturbed atoms come from the gas and exchange energy with the He covering the heater and detector. If the measured sticking coefficient[3] of a few percent for H on He is any indication, very weak signals are expected. It is clear that in this technique the dominant signals can be due to the disturbed evaporating He film itself. The small dimensions of the HSC require fast detectors; conventional transition-edge superconducting bolometers are of no use because of the high magnetic fields. We decided to use the same design for both the heater and bolometer which are planar of area $A=10\times 10$ mm^2 and separated by $l=5$ mm (Fig. 1). A thin foil (14 μm) of Kapton was attached to a thick copper disc with Stycast 1266 epoxy. Gold strip electrodes were vacuum evaporated on the Kapton. A thin layer of "Aquadag"[4] (estimated to be at least 1-μm thick) was spread over the surface as the resistive element. The copper discs are in thermal contact with the mixing chamber, being an integral part of the HSC. The response time of the carbon elements, both electrical and thermal combined, was measured to be about 3 μsec. The bolometer had a responsivity of $\sim 10^4$ V/W with a nominal resistance of 35 kΩ at 400 mK, both fairly insensitive to magnetic field. Noise was preamplifier limited. Usable TOF signals of H↓ could be obtained down to densities of 2×10^{13} cm^{-3}. Heat pulses 10 μsec long were usually used with maximum energy per unit film area of 0.0017 erg/cm^2/pulse. Signals were fed into a Biomation 805 transient recorder connected to a Nicolet 1170 waveform averager. Typically 10^4 sweeps were averaged at an 80-Hz rate; this was transmitted to a PDP/11 computer for further analyses.

In Fig. 2 we show typical TOF results. Figure 2(a) represents a TOF with no H↓ in the cell, thus a pure ^{4}He signal. In 2(b) at the same temperature ($T=400$ mK) the cell is loaded with a density of about 10^{15} H↓/cm^3 (H↓-H↓ mean free path $\simeq 10$ mm, using s-wave scattering length 0.72 Å) and the TOF spectrum due to both H↓ and ^{4}He is obtained. Figure 2(c) shows the isolated H↓ signal, the difference of 2(b) and 2(a). In Fig. 2(d) we show a TOF for an H↓ filled cell at $T=200$ mK. At this temperature it is not necessary to make a background subtraction as the ^{4}He signal which comes from film evaporation (and recondensation

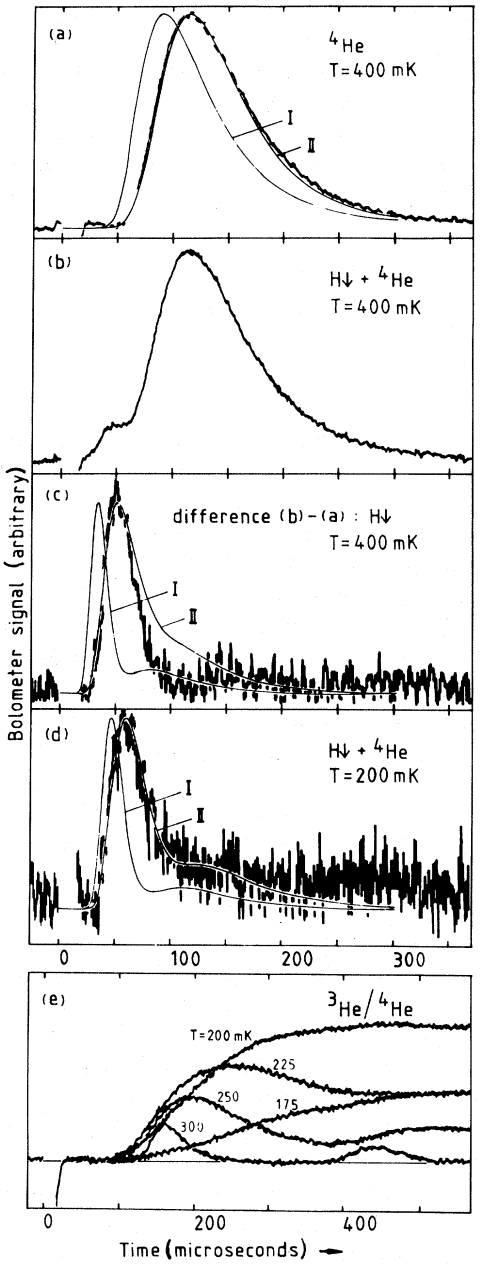

FIG. 2. Series of TOF and theoretical curves described in the text. All TOF's correspond to heat pulses of 0.0017 erg and 10 μsec, except for d which was 0.0072 erg and 15 μsec.

on the detector) is strongly reduced. In our system we can actually measure the temperature of the calibrated carbon heater, and find that in case 2(d) it has risen to over 400 mK during the pulse. The absence of a ^{4}He signal suggests that the ^{4}He film does not follow the carbon in temperature. In Fig. 2(e) we show the response for ^{3}He-^{4}He. Both the mixture and pure ^{3}He showed a very sluggish response. No H↓ signal was observed. At higher temperatures, with densities in the viscous region, sound waves and many reflections could be observed for both ^{4}He and ^{3}He showing that this geometry is suitable for studies of viscous H↓.

To analyze the data, we note that the bolometer is an energy-flux-sensitive detector at a temperature T_b, above ambient temperature T_0 (due to its bias current). In steady state it is continually being bombarded by (and evaporating) atoms assumed to have a Maxwell-Boltzmann distribution (MBD). Let us also assume that during the heat pulse, which starts at time $t=0$ and lasts $\delta t'$, the He film warms up from T_0 to T' and that during this time the H↓ atoms which hit the surface deposit a fraction S_e of their energy and desorb with a MBD corresponding to T'. The energy-loss coefficient S_e is an average which includes inelastic and elastic collisions, as well as those which result in sticking. If the former did not exist, then S_e would be the sticking coefficient. The resultant detector power at time t, for both He and H↓ signals, is $P(t)=P(t,T')-P(t,T_0)$. This represents a signal due to a beam coming from a heater at T' minus that due to one at temperature T_0 (the subtraction signal). Here

$$P(t,T)=S_e^2(m/2\pi kT)^{3/2}\rho l^{-1}v_z^3\int_0^d\int dx\,dy\int_{-v_zy/l}^{v_z(d-y)/l}dv_y\int_{-v_zx/l}^{v_z(d-x)/l}dv_x(\tfrac{1}{2}mv^2+E_c)\exp(-\tfrac{1}{2}mv^2/kT)\delta t' , \tag{1}$$

where $t=l/v_z$, m is the mass, l the separation between heater and detector squares of side d, and for He, $S_e=1$. For H↓, ρ is $n\sqrt{T_0/T}$ with n the density, and for He it is the vapor density at T (proportional to $\exp(-7.15/T)$. For He, E_c is the condensation energy (7.15 K) and for H↓ it is $-2kT_b$. This expression is exact for our geometry and can be evaluated in terms of error functions. The subtraction signal is usually not important for evaporating He films as the rate of film evaporation depends very strongly on the temperature. Plots are shown in Fig. 2 (labeled as I) for a 10-μsec block heat pulse, using the best fit value of $T'\simeq T_0$. We find very poor agreement between experiment and theory, experiment being much slower. The bump in the theoretical TOF for H↓ arises from the subtraction procedure. We compare our results for ^{4}He to those in the literature,[5,6] where TOF's have been studied extensively to see if they exhibit non-Maxwellian behavior due to the excitation spectrum of liquid ^{4}He. Andres *et al.*[6] found the TOF spectrum of He atoms to be approximately Maxwell-Boltzmann with a temperature considerably above ambient. (Our theoretical model reduces to theirs if we use a point heater and ignore the subtraction signal.) The most important difference between our experiment and that of Andres *et al.*, who find $T'>>T_0$, is that our maximum-pulse energy density is at least a factor 150 smaller than their minimum and heating rates are 3000 times lower. The latter means that their heater temperature is very much greater than ambient during the pulse.

All of our results can be understood by assuming that the thermal relaxation time between carbon and the He film is much longer than that of the carbon to the thermal bath. The long time constant can be accounted for by the Kapitza resistance between the Aquadag and He, giving a time constant $\tau=R_kC$ where C is the heat capacity, dominated by the riplons at low temperature. Additionally an anomalously large value for R_k may be expected for thin films, as observed elsewhere.[7] For ^{3}He, C is more than 3 orders of magnitude larger than for ^{4}He in this temperature regime giving enormous time constants in agreement with our sluggish response. We can reproduce our data with Eq. (1) using a time convolution for both the heater and detector, having an exponentially rising and falling pulse with $\tau=11$ μsec at 400 mK. The results are given by curves II and are in remarkably good agreement with experiment. The rise of temperature of the He film was found to be $T'-T_0\simeq 0.5$ mK from an analysis of the beam intensity as well as the TOF shapes, which were less sensitive. The H↓ TOF's could be fitted best with the same temperature, implying that the reflected H↓ assumes the temperature of the He film. For very high-power heat pulses our experiment yields fast TOF's with $T'>>T_0$ as observed elsewhere. This implies that the use of high-power pulses masks the anomalous Kapitza resistance that we

believe to have observed. The energy-loss coefficient for H↓ can be experimentally determined from Eq. (1) by comparing intensities for H↓ and ^{4}He. We find $S_e = 0.20 \pm 0.1$ (three standard deviations), with the main source of error due to large uncertainties in the H↓ density which was not regularly monitored due to our limited filling rates. We compare our results to those of Jochemsen *et al.*[3] who measure a sticking coefficient $S = 0.045 \pm 0.003$. We see that the exchange of energy with the He surface is more efficient than implied by the small value of S. In addition, the shape of the TOF's are related to the velocity dependence of S_e. Although the signal-to-noise ratio of our data does not allow us to make a definite statement, most of the H↓ experimental TOF's had low long-time tails suggesting a decreased S_e for slow atoms.

In conclusion, we have shown that energy can be coupled through the He film to the H↓ gas to disturb the distribution without destroying the sample. A technique is now available to study second sound, etc., if H↓ can be prepared in a superfluid (Bose-condensed) state. This same technique can be used to create high-flux pulsed atomic beams of H↓ at very low temperature. By orienting the beam along a magnetic field gradient the peak of the distribution can be retarded to zero velocity.

We thank the Stichting FOM for financial support.

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