Direct Observation of Quantum Andreev Reflection at Free Surface of Superfluid ^{3}He

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The quantum Andreev reflection has been observed for the first time at the free surface of superfluid ^{3}He-B in the ballistic temperature region by use of a blackbody radiator with an orifice of 0.2 mm in diameter and 1 mm in length. A quasiparticle beam is produced so as to hit the surface at a small angle of 20° where the normal reflection component does not come back to the detector. The observed reflection rate can be explained by a quasiclassical theory combined with the diffuse scattering of the retroreflected particles at the orifice. [S0031-9007(98)05572-0]

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Andreev reflection is one of the most fundamental concepts in superconductor and superfluid ^{3}He, because this process is directly related with the presence of a Cooper pair condensate which plays an important role in BCS theory. It occurs when the quasiparticle excitation from the condensate passes through the place where the order parameter has a spatial change. Then an impinging quasiparticle (quasihole) is reflected as a quasihole (quasiparticle) with nearly the same momentum as that of the original one but with a reversed group velocity. As the reflected excitation in this process retraces its incoming path, it is often called a "retroreflection" and is quite different from a normal one. This phenomenon was first discovered by Mendelssohn and Olsen [1], who observed that the thermal resistance of a superconductor was much larger in the intermediate state than in the Meissner state. Systematic study of the thermal resistance was made by Zavaritskii [2], which helped Andreev [3] to propose this unusual type of quasiparticle scattering process. Since then, various investigations have been made both directly and indirectly with many methods. As an example of such direct measurements, Benistant, van Kempen, and Wyder [4] observed the retroreflection of injected electrons at the interface between a high purity normal metal and a superconductor.

Although ^{3}He superfluidity is similar to superconductivity in many ways, there are significant differences which arise from the electric neutrality of the He atom and, more importantly, from the p-wave pairing. Especially the unconventional type of pairing is thought to cause novel and exciting types of Andreev reflections in superfluid ^{3}He, compared with a superconductor. Theoretical discussions on the reflection in superfluid ^{3}He have been made widely by Kurkijärvi and Rainer [5]. Experimentally there exist several indirect evidences for the presence of such an unusual scattering process, for example, the quantum-slip effect at the boundary of ^{3}He-B [6], the thermal boundary resistance [7], and the damping of vibrating wire [8]. However, a direct observation of the Andreev reflection was not made until quite recently because of no powerful method. A few years ago, Fisher *et al.* [9] developed a blackbody radiator which can produce and detect a quasiparticle beam in the superfluid ^{3}He-B phase. They have used the device to make a direct observation of the Andreev reflection in the presence of the flow field [10] and also at the superfluid A-B interface [11]. One of the other interesting boundaries is the free surface of superfluid ^{3}He. It is expected to be clean and specular because of no impurities and no excitations at ultralow temperatures. Therefore we can compare the experimental results with those predicted from a quasiclassical theory without taking into account the surface roughness. In this paper we present the first direct observation of the quantum Andreev reflection at the free surface of superfluid ^{3}He by use of the blackbody radiator.

In order to observe the Andreev reflection, several conditions must be satisfied. First, it is necessary to cool down the liquid into a ballistic temperature region so that the mean free path of the quasiparticle excitations exceeds the experimental dimension. Second, the liquid ^{3}He outside the radiator should have a good thermal contact with a refrigerant to sweep promptly the excess quasiparticles produced by the beam. The whole experimental cell, designed to satisfy these conditions, was installed in the low field region of our powerful nuclear refrigerator [12]. The heat exchanger in the sample cell consists of five cylindrical well-annealed silver plates on both sides of which a combination of fine platinum (100 Å) and silver (400 Å) powder with a weight ratio of 2:1 is pressed and sintered. The thickness of the sintered powder is about 0.5 mm and there is 0.5 mm open space for liquid between the sintered plates. The surface area per one plate is about 70 m^2, so the total surface area is about 350 m^2. In the cell, a blackbody radiator and several vibrating wires are suspended from its lid. The blackbody radiator is shown in Fig. 1. Its head is made of a silver hemisphere with a 4 mm inner diameter and a 1 mm thickness. On its surface there exists an orifice of 0.2 mm in diameter, whose axis is oriented for a quasiparticle beam to hit the ^{3}He free surface at a small angle of 20°, where the normal reflection component does not come back to the radiator. Inside the radiator two semicircular vibrating wires with 3 mm leg spacing are installed 1.5 mm apart. The first

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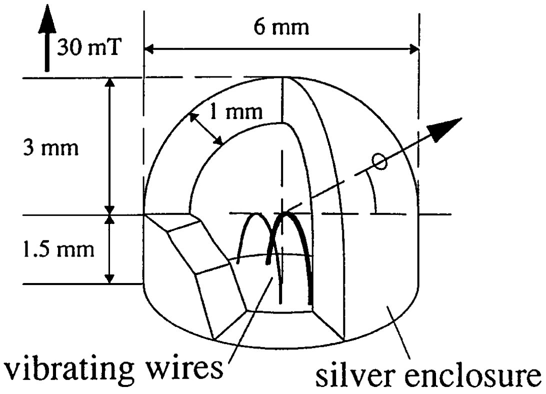

FIG. 1. The blackbody radiator has a silver hemisphere head with a 4 mm inner diameter. It contains two vibrating wires, one to act as a heater and the other to act as a thermometer.

one, 12 μm diameter NbTi, produces a quasiparticle beam and works as a heater. The second one, 4 μm diameter NbTi, is used to measure the quasiparticle density and serves as a thermometer. Outside the radiator the other two vibrating wires are placed; the third one, 4 μm diameter NbTi, is to monitor the liquid temperature there and the fourth, 12 μm diameter NbTi, is to detect the liquid level. A small vertical field of 30 mT is applied to the experimental region as the driving field for the vibrating wire resonators. The full line width at half maximum of the resonance curve in each vibrating wire, (Δf_2), was measured at the thermal equilibrium over the sample cell as a function of the wall temperature which was determined from a platinum NMR thermometer calibrated with a ^{3}He melting curve. The semilog plot of Δf_2 against the inverse wall temperature above 0.2 mK gives us the B phase energy gap of $(1.92 \pm 0.01) k_B T_C$, which is consistent with those by Guénault *et al.* [13] and König *et al.* [14].

Measurements were made for different liquid ^{3}He levels which were adjusted precisely with the fourth vibrating wire and two ^{3}He standard volumes, big and small, at room temperature. When the ^{3}He free surface is high enough to fill up the cell and far from the orifice of the blackbody radiator [case (I)], the emitted quasiparticle beam is scattered at the cell wall over wide solid angle and does not come back to the orifice. The energy flux, $\dot{Q}_{\text{beam}}$, of the order of pW is absorbed by the sintered powder immediately and does not affect the liquid temperature outside the radiator. In a steady state, $\dot{Q}_{\text{beam}}$ is equal to the heater power produced by the heater vibrating wire, $\dot{Q}_{\text{ap}}$. When the ^{3}He free surface is close to the orifice [case (II)], the emitted quasiparticles are retroreflected at the surface and return to the radiator again. Then the temperature inside the radiator becomes steady when $\dot{Q}_{\text{beam}}$ is equal to the sum of the heater power, $\dot{Q}_{\text{ap}}$, and the retroreflected energy flux, $r_A \dot{Q}_{\text{beam}}$, where r_A is the overall Andreev reflection rate ($\dot{Q}_{\text{beam}} = \dot{Q}_{\text{ap}} + r_A \dot{Q}_{\text{beam}}$). In this case $\dot{Q}_{\text{beam}}$ is $1/(1 - r_A)$ times as large as that of case (I) for the same heater power. From this factor, $1/(1 - r_A)$, we can obtain the overall Andreev reflection rate, r_A.

The heater power $\dot{Q}_{\text{ap}}$ is obtained from $I \times V_h$, where I is the (rms) current through the heater and V_h is the in-phase (rms) voltage at the resonant frequency at each current. The emitted energy flux from the box $\dot{Q}_{\text{beam}}$ is given as follows:

$$\dot{Q}_{\text{beam}} = \frac{A}{2} \int_{\Delta}^{\infty} E g(E) [f(E) - f_0(E)] v_g(E)\, dE\,, \quad (1)$$

where $g(E)$, $f(E)$, $f_0(E)$, $v_g(E)$, and A are, respectively, the density of states, the Fermi distribution at T and T_0, the group velocity, and the cross section of the orifice. After some calculations, it is written as

$$\dot{Q}_{\text{beam}} = \frac{1}{2} A N_F v_F \left[k_B T (k_B T + \Delta) \exp\left(-\frac{\Delta}{k_B T}\right) - k_B T_0 (k_B T_0 + \Delta) \times \exp\left(-\frac{\Delta}{k_B T_0}\right) \right]. \quad (2)$$

Here N_F, v_F, and Δ are, respectively, the density of states at Fermi energy, the Fermi velocity, and the B phase energy gap. T and T_0 are, respectively, the liquid temperatures inside and outside the blackbody. They are derived from (Δf_2) of the vibrating wires placed there. As the resonance line was clearly symmetric Lorentzian, Δf_2 was actually estimated from the relation $(\Delta f_2) \times V_t =$ const, where V_t is the amplitude of the vibrating wire on resonance. This relation was checked before and after a series of measurements to remove the experimental systematic errors coming from a cross talk problem. Finally the value of (Δf_2) was corrected for the intrinsic width arising from the wire itself.

Typical raw data are shown in Fig. 2. Figure 2(a) shows the amplitude of the vibrating wire outside the blackbody radiator at a resonant frequency of about 605 Hz. The temperature of the liquid there (T_0) was kept constant at 170 μK within an extremely good accuracy of ± 0.2 μK

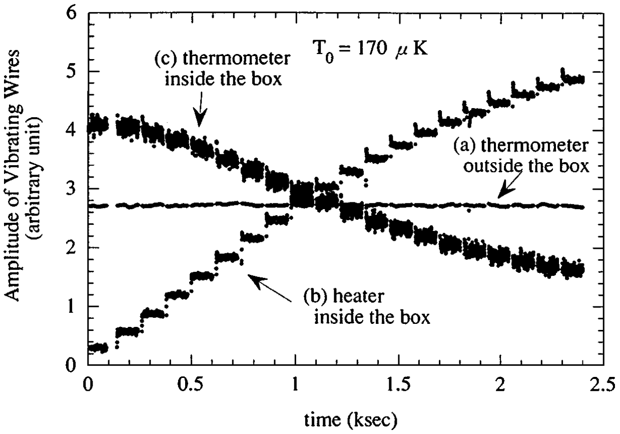

FIG. 2. Amplitude of three vibrating wires monitoring (a) the liquid temperature outside the blackbody radiator, (b) the heater power, and (c) the liquid temperature inside the blackbody radiator. The temperature outside the blackbody is 170 μK.

during a series of measurements by slow nuclear demagnetization. Figure 2(b) shows the amplitude of the heater vibrating wire inside the blackbody radiator at a resonant frequency of about 1.922 kHz. The stepwise structure is due to the increase of the current by 0.071 μA every 120 sec. Figure 2(c) shows the amplitude of the thermometer vibrating wire inside the blackbody radiator at resonant frequency of about 607 Hz with a constant current of about 0.074 μA. The thermal time constant after the increase of the heater current was found to be very short, typically about 1 sec. Now we can calculate T_0, T, and then $\dot{Q}_{\rm beam}$ from Eq. (2) by use of the energy gap in the present Letter. The value of $\dot{Q}_{\rm beam}$ at T_0 of 170 μK is given in Fig. 3 for both cases (I) and (II) as a function of $\dot{Q}_{\rm ap}$. Small scattering of the data is due to the uncertainty limits of the measurements. The main cause arises from our employment of the same excitation current in the thermometer to avoid the variation of the cross talk. Nevertheless the data were reproducible even for a thermal cycle up to 10 K and for the small difference of the free surface level in case (II). Obviously $\dot{Q}_{\rm beam}$ is proportional to $\dot{Q}_{\rm ap}$. This is reasonable because of our smaller $\dot{Q}_{\rm beam}$ than that of Fisher *et al.* [9]. A linear fitting gives us a larger slope in case (II) than in case (I). Similar data were obtained for several temperatures T_0. The temperature dependence of the slope is given in Fig. 4(a) for both cases. For case (I), the emitted particles do not return back into the blackbody, which means that $\dot{Q}_{\rm beam}/\dot{Q}_{\rm ap}$ should be equal to 1, while the obtained value of $\dot{Q}_{\rm beam}/\dot{Q}_{\rm ap}$ is about 5.4, although there exists a slight temperature dependence possibly due to incomplete fulfillment of the infinite mean free path. This indicates that $\dot{Q}_{\rm beam}$ here is overestimated and actually only 18.6% of the excited quasiparticles is emitted from the blackbody radiator. This fact is not so surprising because the mean free path of the quasiparticles is much longer than the orifice size in the present temperature region. A pretty large amount of the quasiparticles entering into the orifice is scattered diffusively at its rough wall and comes back to the blackbody. A similar numerical calculation for the molecular gas flow with an infinite mean free path says that only 20% of the entering molecules passes through the orifice with the aspect ratio used here [15]. Therefore the value of 5.4 is apparent, because a nominal geometrical value of A was used in the calculation of $\dot{Q}_{\rm beam}$ as the cross section of the orifice. The difference of $\dot{Q}_{\rm beam}/\dot{Q}_{\rm ap}$ between the above two cases is important. The error bars in Fig. 4(a) are the largest ones estimated from the fitting in Fig. 3. In spite of such uncertainties, it is clear that the values for case (II) are larger than those for case (I). This indicates that there exists what is called a quantum Andreev reflection at the free surface of superfluid ^{3}He-B. The retroreflection rate in case (II), r_A, is given in Fig. 4(b) as the increment from the average value of 5.4 in case (I).

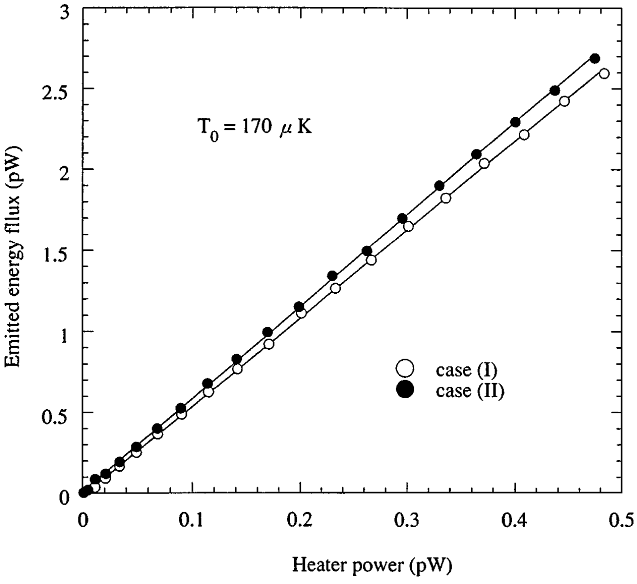

FIG. 3. Heater power dependence of the emitted energy flux at 170 μK. The solid lines are the best fitted ones. In case (I), the emitted particles are scattered over the wide solid angle and they do not return to the blackbody. In case (II), they hit the free surface near the orifice and are retroreflected.

Let us make a rough estimation on the observed reflection rate in the actual experimental situation of case (II) in the ballistic limit. For simplicity, we assume that the

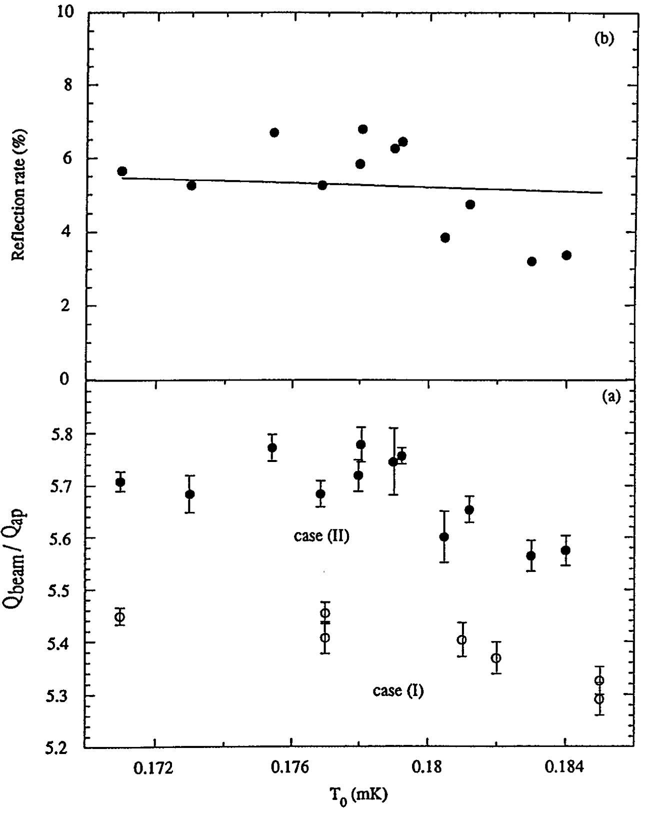

FIG. 4. (a) $\dot{Q}_{\rm beam}/\dot{Q}_{\rm ap}$ for both cases as a function of the liquid temperature (T_0) outside the blackbody radiator. (b) The observed reflection rate as a function of T_0. The solid line is the calculated one which is based on the quasiclassical theory (see text).

angular dependence of the emitted quasiparticles for the present orifice is the same as that of the molecular gas flow with an infinite mean free path [15]. Then nearly half (52%) of the emitted particles hit on the free surface which can be seen directly through an orifice from the blackbody radiator inside. The remaining half is scattered at the sample cell wall over the wide solid angle and its contribution to the retroreflection is supposed to be small. Therefore we are mainly concerned with the former half with an incident angle between 10° and 30°. The corresponding beam spot on the free surface is divided into small regions which have their own incident angle and round trip distance. For each region, the Andreev reflection rate is estimated based on its theoretical energy dependence obtained by Nagato *et al.* in their quasiclassical theory [16]. After summed over all the small regions, the present overall Andreev reflection rate at the free surface is estimated to be about 44%. Thus the particles coming back to the orifice are about $22.8(= 52 \times 0.44)\%$ of the emitted ones. Among them, those going out from the orifice without any collisions and being Andreev reflected at the free surface are about $2.33(= 5.3 \times 0.44)\%$ of the emitted ones [17] and they return back to the blackbody radiator without loss. The remaining 20.5% are diffusively scattered at the orifice wall on their way back. The fraction entering again into the radiator is difficult to be estimated, because the angular distribution of the retroreflected beam is more or less focused and there exists the Andreev reflection probability at the orifice wall. But if we use the transmission rate obtained here for the particles diffusively scattered at the orifice, 17.7% [18], the returning particles into the blackbody radiator are about $3.63(= 20.5 \times 0.177)\%$ of the emitted ones. Totally about 6.0% of the emitted particles are estimated to come back to the radiator. This value is close to the observed one in spite of various assumptions.

The other correction to be made is the quasiparticle scattering during the round trip between the orifice and the free surface. In spite of no experimental data on superfluid ^{3}He, the mean free path (l) of quasiparticles at 0 bar is estimated to be about 36 mm at $0.2T_C$ by combining the theoretical calculation at 21 bars by Einzel *et al.* [19] with the pressure dependence of the Fermi velocity and of the relaxation time. The ballistic condition is certainly satisfied for the diameters of the vibrating wires, about 4 or 12 μm, and the diameter of the orifice of the blackbody radiator, about 0.2 mm. However, the round trip distance ($2d$) is between 5 and 17 mm depending on the incident angle, and this effect is taken into account by use of a factor of $\exp(-2d/l)$ in the numerical calculation. The corresponding loss reduces the obtained value above by only 10% to 17% which depends on the liquid temperature outside the radiator. Finally, the calculated reflection rate in case (II) is given in Fig. 4(b) as a solid line, which is consistent with the observed behavior in spite of a very crude estimation.

In conclusion, the quantum Andreev reflection clearly exists at the free surface of superfluid ^{3}He B. The observed reflection rate can be explained with a quasiclassical theory if we take into account the loss due to the diffuse scattering at the orifice. The shape of the orifice is very important to make a quantitative analysis. Further experiments are eagerly desired for various aspect ratios and for the different surface conditions of the orifice.

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