Blackbody Source and Detector of Ballistic Quasiparticles in ^{3}He-B: Emission Angle from a Wire Moving at Supercritical Velocity

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Using a new quasiparticle detector and source consisting of a blackbody radiator, we have made the first measurements of the divergence of a beam of quasiparticles produced by a vibrating-wire resonator moving at supercritical velocities in superfluid ^{3}He-B at the zero-temperature limit. At velocities just above the critical velocity of $\Delta/3p_F$ we see a very narrow beam directed along the direction of motion of the wire. As the maximum wire velocity increases the beam spreads to saturate at a half-angle divergence of approximately 55° at a maximum velocity of order Δ/p_F.

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The dilute gas of excitations from a superfluid ground state presents one of the simplest many-body assemblies accessible to experiment. Conceptually, experiments are particularly simple in the ultradilute ballistic regime, which for ^{3}He-B corresponds to the temperature range below about $0.2T_c$. Currently accessible temperatures reach down to around $0.1T_c$, where the fraction of particles which are unpaired represents about 10^{-6} of the whole, and mean free paths are measured in kilometers. (Quasiparticle equilibrium, in this case, is thus reached by normal collisions with the enclosing surfaces.) This excitation gas provides the ideal medium for a quasiparticle beam experiment with the three essential components of source, experiment, and detector. Hitherto we have lacked a detector whose behavior we fully understand. However, that problem has now been solved, and it is the purpose of this paper to present the first measurements of the angular spread of quasiparticles emitted by a wire moving at supercritical velocity by the use of a blackbody bolometric detector. A blackbody operating in superfluid ^{3}He-B not only provides superb quasiparticle detection, but in the furnace mode can also generate a finely tunable beam of thermal excitations. With further development the bolometer should provide a very sensitive energy detector, with implications outside superfluidity physics.

The mechanism of pair breaking by macroscopic objects moving through the superfluid has interested us for some time. When a cylinder moves just at the critical velocity [1], $v_c=\Delta/3p_F$, the only states available to the emitted excitations have k vectors aligned with the direction of motion. Consequently, at the onset of pair breaking, a narrow-angle beam of quasiparticles should be emitted in the forward direction and a narrow beam of quasiholes in the rearward direction. As the velocity of the cylinder increases, emission becomes possible over a wider range of angles and the beam should spread. Consider a cylinder moving transversely through the superfluid with velocity $-v$. In the rest frame of the cylinder, the distant bulk liquid moves past at velocity v. For pure potential flow the greatest relative velocity between cylinder and superfluid of $2v$ occurs along the two lines on the surface of the cylinder perpendicular to the direction of motion. Extending the arguments of Lambert [1], excitations may be generated by pair breaking into the normally bound states near the wire which are emitted into the liquid with energy (in the cylinder rest frame) of $2p_Fv$. These excitations are emitted from the cylinder, and hence contribute to the damping, so long as states are available with the same energy in the bulk. The minimum energy of bulk states for k vectors at angle θ to the direction of motion is $\Delta-p_Fv\cos\theta$, where Δ is the bulk gap. Therefore the maximum angular divergence of the beam should be determined by the onset condition: $2p_Fv=\Delta-p_Fv\cos\theta$. The lowest onset velocity for pair breaking is thus $v_c=\Delta/3p_F$, when $\cos\theta=1$, i.e., a narrow beam in the forward and rearward directions. Emission in all directions ($\cos\theta=0$) can occur at $v=\Delta/2p_F$. This simple model gives the correct experimental value for v_c, but hitherto there has been no information on the angular behavior as a function of velocity.

The experimental cell used for these measurements is made of epoxy with a nested cell configuration similar to that described earlier [2]. The experimental arrangement in the inner cell is shown in Fig. 1. The blackbody cavities consist of three $5\times5\times3$-mm^3 cuboidal boxes defined by walls of plastic-impregnated paper. Each box contains a 13-μm and a 4.5-μm NbTi vibrating-wire resonator (VWR) both with a leg spacing of 3 mm. The blackbody radiator consists of a 0.3-mm-diam hole, as shown in the figure. The VWRs inside each box move perpendicularly to the face with the hole. Outside the boxes are four 13-μm-diam NbTi wire VWRs, designated VWR1, VWR2, etc., and arranged such that the active part of the wire is aligned with the central hole. A further 4.5-μm VWR is used as an external thermometer. Each VWR is driven by a frequency synthesizer and the output is analyzed by a lock-in amplifier, all under desktop-computer control.

The experiment consists of three parts: (i) calibration of the blackbodies, (ii) the blackbody as source, and (iii) the beam spread experiment with the blackbody as detector.

(i) To calibrate the blackbody radiators we first consid-

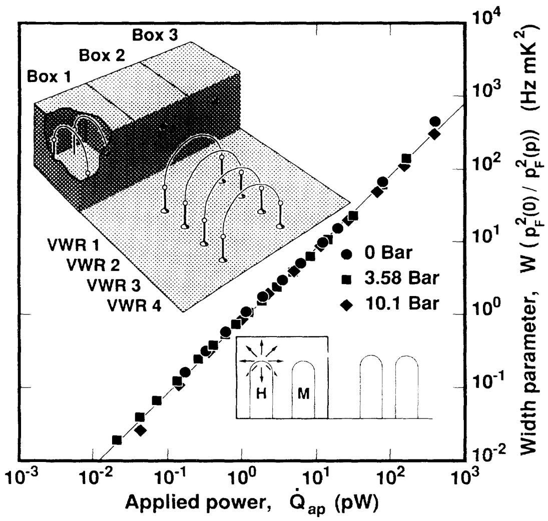

FIG. 1. The calibration of the center box for three pressures. The box is heated by VWR labeled H, which generates the applied power $\dot{Q}_{\rm ap}$. The response is measured by the VWR labeled M, whose width parameter W is derived from the measured VWR width as described in the text. Linearity is obtained over a wide range of $\dot{Q}_{\rm ap}$ and of pressure. Inset: The arrangement of the blackbody radiators and the four external 13-μm NbTi VWRs. Each box contains one 4.5-μm NbTi and one 13-μm NbTi VWR as shown.

er the VWRs in each box. The damping force per unit length of a wire moving at velocity v in the B phase due to the scattering of thermal quasiparticles can be written [3] $F=2\gamma d p_F \langle n v_g\rangle p_F v/k_B T$, where d is the diameter of the wire, γ is a constant of order unity, and the quantity $\langle n v_g\rangle$, loosely termed the "quasiparticle flux," is the integrated product of the occupied quasiparticle or quasihole states multiplied by the appropriate group velocity, $\int g(E)f(E)v_g(E)dE$. This damping force is directly related to the frequency width Δf_2 of the VWR resonance via a second constant of order unity to give $\Delta f_2 = \gamma'\langle n v_g\rangle d p_F^2/\pi m k_B T$ where m is the mass per unit length of the wire. Hence the frequency width multiplied by the temperature is proportional to the quasiparticle flux.

Calibration of the boxes means the determination of the constant γ'. We heat the central box by driving the 13-μm VWR inside at high velocity while monitoring Δf_2 of the more sensitive 4.5-μm VWR. Excitations transit the box several hundred times before being able to escape through the orifice. This, coupled with the decreased quasiparticle-quasiparticle mean free path at the elevated temperature in the box, ensures that thermal equilibrium is rapidly attained. The power developed in the driven VWR is calculated from the drive current and the inphase voltage generated. The frequency width of the measuring VWR rapidly reaches a stable value after the heating level is changed, since the resonant frequency of the heating VWR is 1 kHz, whereas the time constant of the box, governed by the hole size, is about 0.1 s. At equilibrium, the number density of quasiparticles inside the box is approximately constant and therefore the total power $\dot{Q}_T$ entering the box must be balanced by the power emitted from the hole.

Assuming thermal equilibrium of the excitation gas in the box, the power $\dot{Q}_T$ emitted from the hole is given by $\dot{Q}_T = 2(\langle n v_g\rangle/4)\tilde{E}A$, where the factor 2 accounts for quasiparticle and quasihole contributions, A is the area of the hole, and $\tilde{E}$ is an average thermal energy calculated as follows:

$$\tilde{E}=\langle n v_g E\rangle/\langle n v_g\rangle = \frac{\int g(E)f(E)v_g(E)E\,dE}{\int g(E)f(E)v_g(E)dE} = \Delta + k_B T\,.$$

Rearrangement yields the following relationship between the frequency width inside a box and the total power entering: $\Delta f_2 T\tilde{E} = \gamma'(2dp_F^2/\pi m A k_B)\dot{Q}_T$. The power entering the box has two components: that supplied by the heating VWR, $\dot{Q}_{\rm ap}$, and that leaking from the plastic walls. (Heat entering through the hole from outside is negligible.) Subtraction from the measured $\Delta f_2 T\tilde{E}$ of the value of this same quantity measured at zero applied heating yields a width parameter W which eliminates the heat leak from the walls. We can thus write $W = \gamma'(2dp_F^2/\pi m A k_B)\dot{Q}_{\rm ap}$. A plot of W versus applied power should therefore follow a linear relation and yield the value of the constant γ'.

Figure 1 shows the results of this experiment. Three pressures were chosen to span a factor of 2 in T_c. The results are plotted as W scaled by the pressure dependence of p_F^2, versus the applied power $\dot{Q}_{\rm ap}$. T and $\tilde{E}$ are expressed in mK, on the Greywall [4] temperature scale. Values for p_F are taken from Wheatley [5]. Impressively, the data for all three pressures lie on a single line of slope unity covering 5 orders of magnitude, providing solid confirmation that our model is correct, and also that the excitation gas in the box does attain thermal equilibrium, since the temperature is critical for the fit. The value for γ' given by the line is 0.51 ± 0.05, i.e., of order unity as expected.

(ii) After calibrating the boxes, we use the central blackbody as a source to direct a beam of excitations along the line of external VWRs. By detecting the damping effect on the wire motion we verify that the quasiparticle flux in the beam corresponds to the density inside the blackbody radiator.

The interaction of a unidirectional beam with a moving wire is nontrivial. Naively, one might expect the beam to exert a constant force on the wire independent of the wire velocity, leading merely to a change in the equilibrium position. In fact, when a beam carrying an equal flux of quasiparticles and quasiholes impinges on a stationary wire the force exerted is effectively zero, since in a normal scattering process a quasihole will pull whereas a quasiparticle will push. However, when the wire is moving this cancellation no longer occurs. The flow field around the moving wire deflects some of the incoming excitations by Andreev processes and only a fraction of the excitations reach the wire surface [3]. The resultant net force exerted on the moving wire is always opposed to the direction of motion, since during motion towards (away from) the beam source, an excess of quasiparticles (quasiholes) reaches the wire surface. Normal scattering then gives rise to net force away from (towards) the beam source. The final result is that the moving VWR experiences a very large damping force when moving in the path of the incoming beam.

The source of the beam is the central box. The 13-μm VWR inside is driven on resonance, generating a gas of excitations within the box to provide the beam emitted from the hole. This beam has a characteristic temperature T_b, the temperature in the box. The excitation flux carried by the beam is deduced from the frequency widths of the four external 13-μm NbTi VWRs aligned on the central hole as shown in Fig. 1.

The frequency width of an external VWR has three components, the contribution from intrinsic damping, that from the thermal distribution of quasiparticles outside the box, and finally the required contribution from the beam. To eliminate intrinsic damping we subtract from the measured width the width at zero power to yield $\Delta f_2'$. We then make the assumption that all four wires behave indentically (which is correct to within a few percent). With the beam on, we can subtract the effect of the background temperature by looking at the difference between the $\Delta f_2'$ of the Nth VWR and that of the most distant, VWR4: $\Delta f_2(N)' - \Delta f_2(4)' = \Delta f_2(N)'_{\text{beam}} - \Delta f_2(4)'_{\text{beam}}$. The left-hand side of this equation is measured, while the right-hand side can be deduced from the expected properties of the beam as follows.

From the arguments of the previous section, the contribution to Δf_2 from the beam with a quasiparticle flux $\langle nv_g \rangle_b$ and effective temperature T_b is $\Delta f'_{2\text{beam}} = \gamma_b \langle nv_g \rangle_b dp_F^2 / \pi m k_B T_b$. At the position of a VWR (number N), at a distance r_N directly in front of the central box, the beam flux should be given by $\langle nv_g \rangle_b \equiv \langle nv_g \rangle A / 4\pi r_N^2$ where $\langle nv_g \rangle$ is the flux inside the box. Hence we have $\Delta f_2(N)'_{\text{beam}} = \gamma_b(N) dp_F^2 \dot{Q}_{\text{ap}} / 2\pi^2 m k_B T_b \times r_N^2 \tilde{E}$, and finally

$$[\Delta f_2(N)' - \Delta f_2(4)'] \frac{T_b}{p_F^2} = \frac{d}{2\pi^2 m k_B} \left(\frac{\gamma_b(N)}{r_N^2} - \frac{\gamma_b(4)}{r_4^2} \right) \frac{\dot{Q}_{\text{ap}}}{\dot{E}}.$$

The left-hand side represents the measured reduction in beam flux going from VWRN to VWR4, predicted to be proportional to $\dot{Q}_{\text{ap}}/\tilde{E}$, i.e., the flux emitted from the hole.

The measured result is shown in Fig. 2. The data for VWRs 1 and 2 fall on two straight lines of gradient unity for all three pressures, again covering several decades. The values for γ_b obtained are approximately 1.1 for VWR1 and 0.9 for VWR2 (assuming a similar value for VWR4), of the expected order of magnitude and identical for both wires within experimental uncertainty. This again indicates that our thermal quasiparticle gas model is consistent.

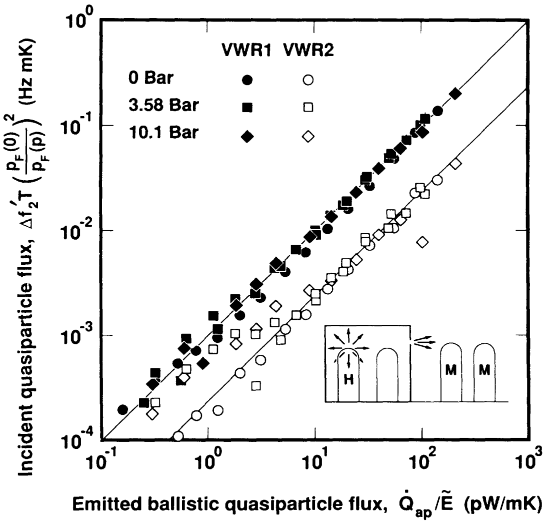

FIG. 2. The central box as a blackbody radiator at three pressures. The beam flux measured by VWRs outside the box is found to be proportional to the flux ($\dot{Q}_{\text{ap}}/\tilde{E}$) generated inside the box.

(iii) We now have all the information on the performance to measure the angular spread of the beam of excitations emitted by a wire moving above the critical velocity v_c. The experiment consists of driving one of the external VWRs above v_c and bolometrically detecting the energy flux in the beam entering the blackbodies. When the wire is driven just above v_c the initial narrow beam should be directed straight into the hole of the central blackbody within the geometrical accuracy of the experiment (not perfect since the shape of a 13-μm wire is not easily controlled). In this case 50% of the energy emitted by the wire should be detected in the central box (the other 50% is lost to the oppositely directed beam). As the beam spreads with increasing velocity, the fraction of energy intercepted by the hole should fall, until in the extreme case of isotropic emission the hole would intercept only a fraction $A/4\pi r_N^2$ of the emitted energy.

The 4.5-μm VWRs inside the boxes can detect the incoming energy flow to a resolution of order 10^{-2} pW (see Fig. 1). The diameters of the holes in the boxes are of order 0.3 mm, and therefore the energy flux incident on the holes from external quasiparticles can be resolved to about 0.1 pW mm^{-2}. Since the external VWRs can be driven up to 1 nW, the blackbodies have ample resolution for the experiment.

The measurements are made as follows. The nearest VWR (1) is driven on resonance, producing the quasiparticle beam. The power dissipated $\dot{Q}_{\text{ap}}$ is measured as before. The beam power is detected by the change in frequency width of the VWRs inside the central and side

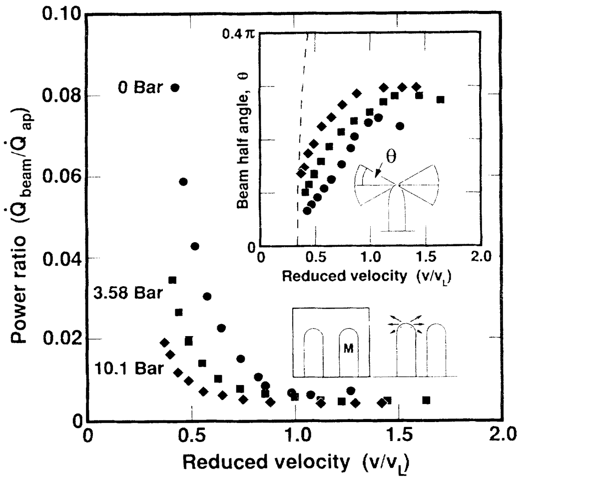

FIG. 3. The fraction of power emitted by VWR1 which is received by the blackbody, plotted as a function of the peak velocity of the resonator for three pressures. The velocities are scaled by the Landau velocity, $v_L=\Delta/p_F$. Inset: The effective beam angle vs velocity derived from these data.

boxes. The results obtained are analyzed on the following model.

The total power entering a box can be written $\dot{Q}_T=\dot{Q}_0+\dot{Q}_{ex}+\dot{Q}_{beam}$, where $\dot{Q}_0$ is the power entering the box with no applied power, $\dot{Q}_{ex}$ is the contribution from the increase in the density of thermal quasiparticles outside when power is applied to the source, and finally $\dot{Q}_{beam}$ is the power entering the hole from the beam. From above, the total power entering box M is related to the VWR width by $(\Delta f_2 T\tilde{E})_M=(\gamma' 2dp_F^2/\pi m k_B)\times(\dot{Q}_T/A)_M$. We again eliminate the zero-power contribution by subtracting the quantities $\Delta f_2 T\tilde{E}$ with and without applied power, to give the width parameter $W=(\Delta f_2 T\tilde{E})_{power}-(\Delta f_2 T\tilde{E})_0$, as in experiment (i) above. We eliminate the extra thermal term $\dot{Q}_{ex}$ by subtracting the width parameter measured in a side box (box 3, out of the direct beam) from the value measured for the central box (box 2 in the full beam):

$$W_2-W_3=\gamma'\frac{2d}{\pi m}\frac{p_F^2}{k_B}\left\{\left(\frac{\dot{Q}_{beam}}{A}\right)_2-\left(\frac{\dot{Q}_{beam}}{A}\right)_3\right\},$$

where γ' is assumed to have the same value for the VWRs in boxes 2 and 3.

This expression effectively gives the beam power entering the central box 2. (From the geometry of the cell layout, the beam power entering box 3 is at most 15% of that entering box 2, even for the extreme case of isotropic emission from VWR1.) Hence we can obtain the fraction of the total power emitted by VWR1 which enters box 2, $\dot{Q}_{beam}/\dot{Q}_{ap}$. This fraction for three pressures is plotted in Fig. 3 as a function of the maximum velocity v of the wire. There are no data at low v as the beam is too narrow to "find" the hole in the central box. Nevertheless the effect of beam spreading is clearly seen. At low v the beam is narrow and a high fraction enters the box, whereas as v increases, the beam spreads and the fraction entering the central box falls.

From the power-ratio data we can estimate an effective beam spread, characterized by a half-angle θ. The power fraction from a *uniform* conical beam would be equal to the areal ratio $A/4\pi r^2(1-\cos\theta)$. This effective angle is plotted in the inset to Fig. 3. Once a velocity is reached where the box intercepts the beam, θ rises almost linearly and saturates at about 0.3π. This angle can be compared in a simple-minded way with the greatest possible emission angle which is given by the onset condition $2p_F v=\Delta-p_F v\cos\theta$. Clearly the beam is much narrower than this, suggesting that the majority of the quasiparticles emitted travel at angles close to the direction of motion of the wire, even at high velocities (which is not unexpected since there are many more possible emission processes at lower angles).

A surprising feature of the data is the large variation with pressure. The beam widths are greater for the same values of v/v_L at higher pressures. Oddly enough the measured value of θ appears roughly the same at all three pressures for the same *absolute* velocity, v. We have no explanation for this dependence at present.

This straightforward experiment puts us in a position to construct more ambitious beam devices in which two opposed blackbody radiators in line can be used as the source and detector with an experiment in between. Among many possible experiments the most appealing might be the direct observation of the deflection of a beam by superflow.

One final remark about the blackbodies themselves; these must be the coldest bolometers ever used. Given some more development work on response time and background heat leak, we believe such devices may have further applications in very-low-level energy detection.

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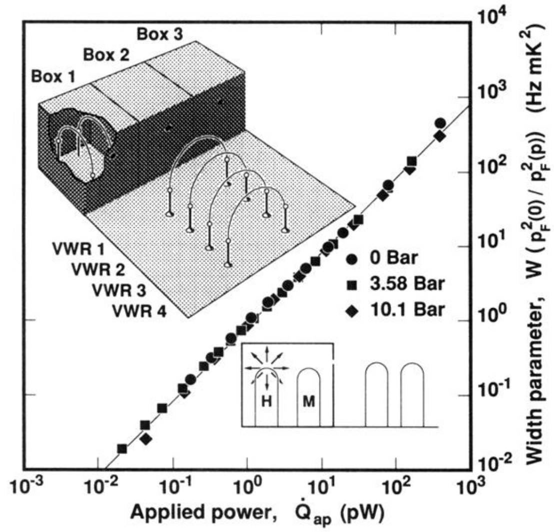

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