Potential Dark Matter Detector? The Detection of Low Energy Neutrons by Superfluid ^{3}He

D. I. Bradley, Yu. M. Bunkov,* D. J. Cousins, M. P. Enrico, S. N. Fisher,* M. R. Follows, A. M. Guénault,
W. M. Hayes, G. R. Pickett, and T. Sloan
School of Physics and Chemistry, Lancaster University, Lancaster LA1-4YB, United Kingdom

(Received 26 January 1995)

Using an existing experiment we have demonstrated in a pilot study that superfluid ^{3}He at 100 μK can be used as a nuclear recoil detector sensitive to neutron and γ interactions depositing energies down to a few hundred eV. The deposited energy is converted to ^{3}He quasiparticles which are detected by their damping effect on a vibrating wire resonator in the liquid. The system can be calibrated independently but a convenient fixed point is provided by the exothermic reaction $n + {}^3_2\text{He} = p + {}^3_1\text{H} + 764$ keV. Given the great potential for improvement we propose that the system might make a sensitive weakly interacting massive particle detector.

PACS numbers: 29.40.Ym, 67.57.Bc, 95.35.+d, 95.55.Vj

A favored candidate for the missing mass in the Universe is a sea of weakly interacting massive particles (WIMPs). Several experiments are currently searching for nuclear recoils from collisions with such objects [1]. To identify their nature it will be necessary to observe nuclear recoils from a variety of nuclei with different spins [2]. Hitherto most target nuclei used have had either zero spin or spin carried by unpaired protons. In this paper we describe the first demonstration that nuclear recoils to below 1000 eV can be detected in superfluid ^{3}He, with the potential for improvement to much lower energies. Furthermore, the nuclear spin is carried here by the neutron and, therefore, superfluid ^{3}He may prove to be a valuable target material for use as a WIMP detector.

Discrimination between nuclear recoils and electrons recoiling from γ-ray interactions may be possible by a measurement of the ionization energy released [1]. One way to achieve this is by monitoring the fraction of the energy liberated as ionized particles. This means measuring both the total energy released and the ionization created by the interactions. For measuring the small total energies from recoil interactions, various cryogenic detectors have been proposed and/or tested, in which the deposited energy is released as a shower of characteristic excitations which can be subsequently detected.

Leaving aside for the moment the problem of distinguishing between ionization and total deposited energy, if we are interested in the highest sensitivity to deposited energy, why not simply employ excitations of the lowest possible energy? One working substance, with excitations of much lower energies than exploited hitherto, is superfluid ^{3}He. As we have previously suggested [3,4], superfluid ^{3}He provides an ideal working material for the detection of low energy recoil interactions. First, the "working fluid" is simple, consisting only of the coherent macroscopic superfluid ground state and an extremely dilute gas of excitations. Second, the excitations have energies comparable to that of the superfluid energy gap $\Delta = 1.4 \times 10^{-7}$ eV, virtually the lowest which we can currently utilize. Third, at the lowest currently accessible temperatures, ≈ 100 μK, the excitation density is about 1 per 10^{10} atoms and falls exponentially with temperature as $\exp(-\Delta/k_BT)$. The total thermal energy content of the liquid at 100 μK is only 160 keV/cm^3 and, with the rapid temperature dependence, this value has fallen to 2 keV/cm^3 by 80 μK. Thus the enthalpy can be adjusted over a wide range by the choice of operating temperature. Finally, discounting possible exotic clusters, the only significant solute is ^{4}He. Extrapolation of the known high temperature solubility of ^{4}He in liquid ^{3}He to 100 μK suggests that ^{4}He is only soluble to 1 part in 10^{2000}. Therefore, the purity in cubic centimeter volumes can be taken as absolute.

To make a practical detector from superfluid ^{3}He we need a working volume of the liquid where the event can occur. We need to detect the quasiparticle gas so produced and finally we must provide a mechanism for reabsorbing the excitations to reset the system to the waiting state. The most sensitive method currently available for detecting the quasiparticle gas exploits the anomalously high damping effect of the gas on a mechanical resonator which varies at low temperature as $\exp(-\Delta/k_BT)$ [5]. In the present work we use a vibrating wire resonator, a thin wire bowed into an approximately semicircular loop a few millimeters in diameter anchored at the ends [6]. There is a vibration mode in which the loop oscillates perpendicular to its plane about the anchor points. In the presence of a modest magnetic field this mode can be excited by an ac current of the appropriate frequency flowing around the loop. If the wire is superconducting, the resistance is zero and the voltage across the ends of the wire gives a direct measure of the vibration velocity (from the cutting of flux lines by the motion in the field). Since the density of the quasiparticle gas at the operative temperature corresponds to a good vacuum, to ensure that the damping effect of the quasiparticles on the resonator is greater than the inherent self-damping, the wire diameter cannot be greater than a few microns.

0031-9007/95/75(10)/1887(4)$06.00

At low amplitudes the response of the resonator is linear and a measurement of the frequency width (or the inverse height) of the resonance yields directly the damping and, therefore, the quasiparticle density. Thus to monitor the density we simply set the resonator on its resonant frequency and record the amplitude of the oscillation. Since the excitation density is measured directly in the working material, multiple chambers may be stacked to yield a large subdivided volume.

By using two existing experimental cells, designed for other experiments but with all the elements described above, we have made a pilot study of the detection of neutrons and γ-ray photons. The important feature of both cells is a quasiparticle "blackbody radiator" [7,8], i.e., a leaky quasiparticle "box." The device consists of a small copper box (volume ≈ 0.1 cm^3 containing about 0.008 g of liquid ^{3}He) immersed in a larger volume containing liquid ^{3}He and thin plates of the copper nuclear-cooling refrigerant. One wall of the box carries a small hole (diameter ≈ 0.3 mm). Inside are two vibrating wire resonators, one to act as a heater and one as a thermometer. For the original application the superfluid ^{3}He inside the box can be heated to emit a beam of thermal excitations from the hole or can detect an external flux of excitations incident on the hole via the induced temperature rise inside.

It is the high sensitivity of this device to an influx of energy which we exploit in the detection of ionizing radiation, which proceeds as follows: A particle interacts inside the box, heats the liquid, and causes a transient dip in the recorded amplitude of the thermometer resonator. The cloud of quasiparticles produced diffuses out of the hole and the amplitude recovers. The thermal time constant of the box is governed by the size of the hole through which the quasiparticles escape and in the present case is a few tenths of a second at the lowest temperatures. Despite the thinness of the wire the Q factors of the resonators are still rather high at the lowest temperatures, $\approx 10^4$, giving time constants of several seconds which largely determine the time constant of the response.

The results reported here were obtained in an experimental cell previously used for Andreev reflection studies [8], installed in the smaller Lancaster nuclear refrigerator [9]. The experimental configuration is shown in Fig. 1. The voltage output of the resonators is detected by a lock-in amplifier with a SQUID preamplifier. The lock-in output is fed to a data logging system to give a continuous readout of signal amplitude as a function of time. Any interaction within the superfluid in the box is seen as a dip in the measured resonator voltage. To put such signals on a quantitative basis we need to calibrate the response in terms of deposited energy. This is no simple matter. The thermal Kapitza resistance between a solid and the superfluid is so high at these temperatures that it is impossible to introduce a pulse of heat into the liquid by means of an Ohmic heater. Fortunately, we can generate short pulses of heat directly in the liquid by exciting the heater wire for a few milliseconds. This heats the excitation gas by mechanical collisions and pair breaking. We monitor the voltage generated by the motion of the heater wire and can calculate the input energy from the product of the drive current and in-phase response voltage over the period of the pulse $\int VI\,dt$. This must be done with care since the shortness of the pulse means that the response is increasing during the whole period. Fortunately there are two independent means of checking the calibration as discussed below.

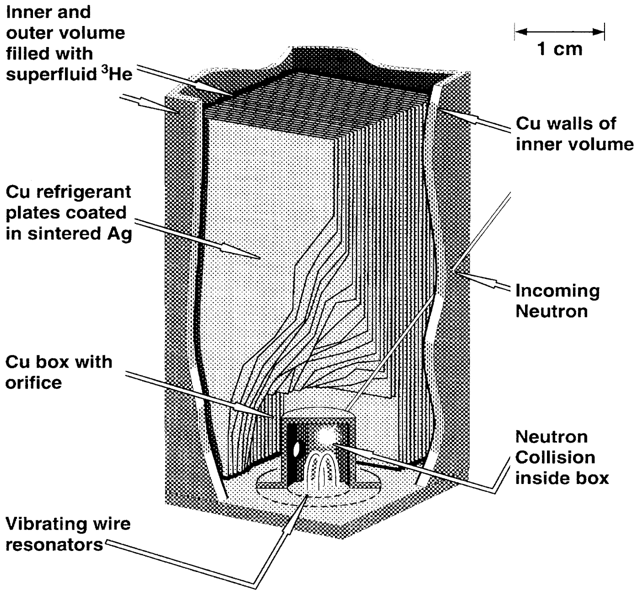

FIG. 1. The inner cell showing outer volume containing liquid ^{3}He and the copper plate refrigerant. At the bottom in the center is the cylindrical copper box containing the superfluid ^{3}He working fluid.

We have tested the sensitivity to ionizing radiation by using a 10 μCi Na^{22} γ-ray source and a 100 mCi americium-beryllium (AmBe) neutron source, positioned at distances of order 1 m from the experimental cell. The ^{22}Na source emits monochromatic γ rays of 0.511 and 1.28 MeV, and the AmBe source emits neutrons with a continuous spectrum from 1 to 10 MeV with a low energy tail down to 0.1 MeV. The AmBe source also emits some γ rays, mainly of energy 4.43 MeV, approximately in the ratio of one γ per two neutrons.

A typical output of the resonator at 112 μK with the AmBe neutron source situated 1.2 m from the ^{3}He is shown in Fig. 2. The upper figure shows the running output of the resonator in volts. The sudden fall in the signal and exponential return caused by a scattering event is clearly seen. The output is typical but this particular section is illustrated since it contains two particularly energetic events. The largest event seen in the figure has reduced the signal from 7.5 to 2 V, almost completely

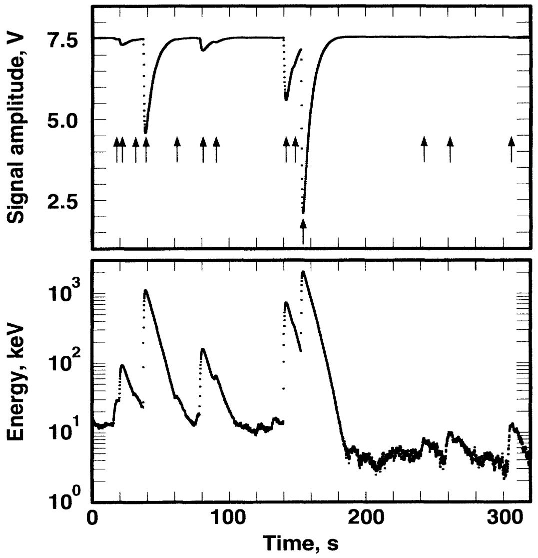

FIG. 2. Upper figure: a trace of voltage vs time for the amplitude of the thermometer resonator in the copper box. The arrows mark the positions of the most obvious events. Lower figure: the same trace plotted on a logarithmic scale after background subtraction. The scale gives the deposited energy corresponding to the peak heights.

flattening the resonator output. The lower figure shows the corresponding signals plotted on a logarithmic scale after background subtraction. The signal decays (except for the very large event) are quite accurately exponential with a fall time of ~5 s.

We can calculate the expected time evolution of the resonator. The thermal time constant of the box (i.e., the quasiparticle escape time) depends only on the quasiparticle group velocity and geometry and can be calculated *a priori* to within 20% (including a 10% uncertainty in the volume). We know the response time of the wire resonator and the heat capacity of the superfluid. We can, therefore, calculate the time evolution of the response to 20%, and within this error we find agreement with the observed time evolution which gives us confidence that our temperature scale and energy calibrations are consistent.

Figure 3 shows an output with the source removed. The number of detected events is much smaller, but we still see low energy events. The two events shown in the figure correspond to energies of 40 and 5 keV. It can be seen that signals down to 1 keV of energy are detectable directly from the raw continuous output of the resonator. Further, by observing the in-phase and quadrature signals from the resonator on an x-y output, we can distinguish considerably lower energy events which follow a characteristic orbit quite distinct from the random noise.

Figure 4 shows energy spectra for (a) the neutron source, (b) the γ source, and (c) no source. The background and γ sources show similar shaped spectra falling rapidly with increasing energy. The neutron spectrum also falls with energy but more slowly than the γ spectrum, and we also see a large peak at ~800 keV.

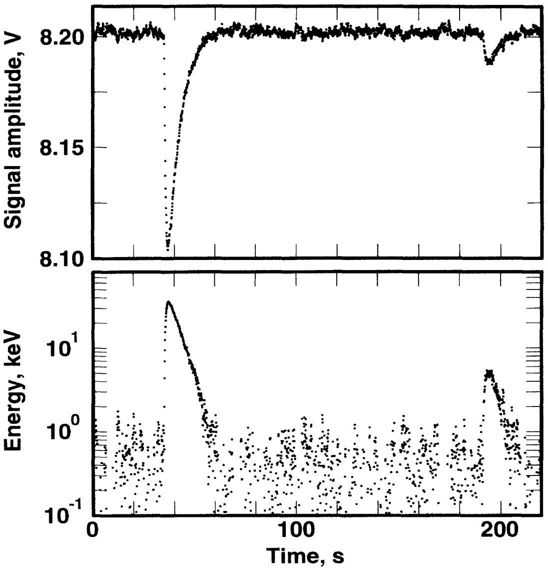

FIG. 3. A similar trace to that of Fig. 2 for a background run with sources removed. Two events, ~40 and ~5 keV, are clearly seen.

The continuous part of the neutron spectrum arises mainly from n-^{3}He elastic scattering. Monte Carlo simulation predicts a shape roughly consistent with that observed. The peak at ~800 keV arises from low energy neutrons

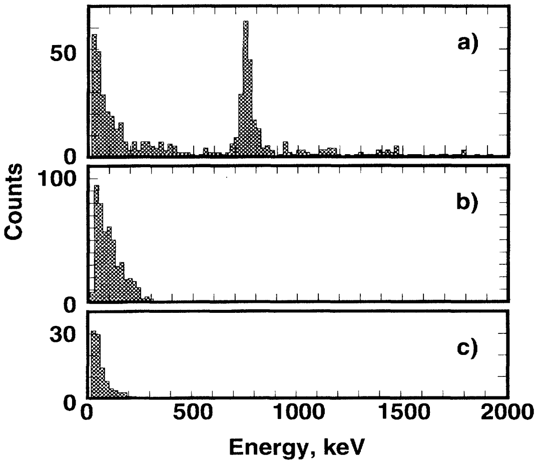

FIG. 4. Energy spectra for (a) neutron, (b) γ source, and (c) no source. The two source spectra taken over 4 h and the 43 h background spectrum have been normalized to 15 000 s for comparison. The narrow peak in the neutron spectrum (a) corresponds to the exothermic $n + {}^3_2\mathrm{He} \rightarrow p + {}^3_1\mathrm{H}$ capture process discussed in the text. The energy scale has been fixed by the accepted 764 keV value for this process.

undergoing the nuclear reaction $n + {}^3_2\text{He} \rightarrow p + {}^3_1\text{H}$ which releases an energy of 764 keV. This further confirms our energy calibration from the mechanical heating of the liquid which puts this peak at 900 ± 150 keV.

The cross section for the $n + {}^3_2\text{He} \rightarrow p + {}^3_1\text{H}$ reaction increases with decreasing neutron velocity down to thermal energies such that the mean free path in liquid ^{3}He becomes less than 1 cm at energies below 300 eV. One would not expect neutrons to be produced at such low energies directly from the source. However, they can be produced indirectly by collisions with the surrounding material of the cryostat which amounts to several cm of various metals. Roughly 3% of the direct flux slowed to such energies would account for the observed intensity of the peak. Such a fraction of slow neutrons in the vicinity of the ^{3}He detector does not seem implausible.

The γ-ray spectrum can be explained by electron recoils produced by Compton scattering. The range of such recoils becomes greater with increasing energy and, therefore, the limit of the size of the ^{3}He container provides a natural, upper cutoff at ~100 keV energy. Similarly the major contribution to the background is probably also due to γ rays originating from radioactive trace elements, hence the similarity in the shapes of the γ and background spectra. It is worth noting at this point that the events recorded in the background measurements yield the radiation heat influx to the 0.1 cm^3 volume of ^{3}He which corresponds to 10^{-16} W. This method may provide the basis for a sensitive bolometer for background radiation in general.

To conclude, we have detected the thermal energy from nuclear recoils in superfluid ^{3}He for the first time. With an existing experiment we can detect signals below the 1000 eV level. This leads us to speculate whether this system might be of interest as a dark-matter detector. The ^{3}He nucleus is a possible candidate nuclear target for dark-matter detection for particles with spin-dependent interactions where high mass nuclei bring no advantages of coherent scattering [10]. There are several things we can do to improve the current performance. (We should emphasize that the current experiment is rudimentary in the extreme.) First, the resonators can be improved. We could use submicron wire since the sensitivity not only increases inversely as the wire diameter increases, but, further, a higher sensitivity gives a lower Q and thus a faster response. (The present 4.5 μm resonators are so slow that only 10% of the increase in quasiparticle density after an event is followed.) Second, the resonators may also be operated in higher ambient magnetic field to give a proportionately larger output. Third, with some improvement to the design the boxes could be operated at lower temperatures, since the sensitivity varies exponentially with T^{-1}. With these changes an overall improvement of 5 orders of magnitude should be achievable, say to around 1 eV/g. For a practical dark-matter experiment much larger masses are needed. Increasing the box size clearly decreases the sensitivity. Say we aim for a sensitivity of 10 eV, then on the above estimates we may use a box as large as $5 \times 5 \times 5$ cm^3 containing 10 g of ^{3}He. A hundred such boxes would yield a 1 kg detector, which would be adequate for a dark-matter detection. While a volume of superfluid ^{3}He as large as this has not been cooled previously we see no great drawbacks in developing such an apparatus with current knowledge. Be that as it may, we certainly believe that superfluid ^{3}He as a medium for particle detection justifies further experimental attention.

We would like to acknowledge the technical backup provided by I. E. Miller and M. G. Ward. This work was supported by the UK SERC under Grants No. GR/G38801 and No. GR/H95839 and EPSRC under Grant No. GR/J29824.

---

*Present address: Centre de Recherche sur les Très Basses Temperatures, CNRS, 25 Avenue des Martyrs, 38042, Grenoble Cedex 9, France.

[1] P. F. Smith and J. D. Lewin, Phys. Rep. **187**, 203 (1990).
[2] J. Ellis and R. A. Flores, Nucl. Phys. **B308**, 883 (1988).
[3] G. R. Pickett, in *Proceedings of the Second European Workshop on Low Temperature Devices for the Detection of Low Energy Neutrinos and Dark Matter,* edited by L. Gonzalez-Mestres and D. Perret-Gallix (Editions Frontières, Gif-sur-Yvette, 1988).
[4] Yu. M. Bunkov, S. N. Fisher, H. Godfrin, A. M. Guénault, and G. R. Pickett, in Proceedings of the 1994 Toledo Conference on Dark Matter and Neutrino Detectors (to be published).
[5] S. N. Fisher, A. M. Guénault, C. J. Kennedy, and G. R. Pickett, Phys. Rev. Lett. **63**, 2566 (1989).
[6] A. M. Guénault, V. Keith, C. J. Kennedy, S. G. Mussett, and G. R. Pickett, J. Low Temp. Phys. **62**, 511 (1986).
[7] S. N. Fisher, A. M. Guénault, C. J. Kennedy, and G. R. Pickett, Phys. Rev. Lett. **69**, 1073 (1992).
[8] M. P. Enrico, S. N. Fisher, A. M. Guénault, G. R. Pickett, and K. Torizuka, Phys. Rev. Lett. **70**, 1846 (1993).
[9] D. I. Bradley, M. R. Follows, I. E. Miller, R. Oswald, and M. G. Ward, Cryogenics **34**, 549 (1994).
[10] J. Engel, Phys. Lett. B **264**, 114 (1991).