Creation and Identification of R^- Rotons in Liquid ^{4}He and an Estimate of Their Probability for Quantum Evaporation

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A beam of R^- rotons, i.e., rotons which have oppositely directed group velocity and momentum, is created by condensing an atom beam onto the surface of liquid ^{4}He. R^- rotons are identified by quantum evaporation and their time of flight. Measured signal shapes agree well with those modeled. Signal sizes are compared with those from atoms specularly reflected from the He surface, from which it is estimated that the quantum efficiency for the condensation or evaporation process is high and of the order of 0.5 for angles of incidence where mainly rotons are created. R^- rotons can specularly reflect from a solid-liquid He interface with high probability, if the interface is particularly good.

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Rotons with negative group velocity (R^- rotons) are particularly interesting as they should behave unconventionally when they interact with surfaces or with other excitations. Although we know that R^- rotons exist from inelastic neutron scattering and thermodynamical measurements, they have not been created in an identifiable way nor have their dynamics been measured. In this Letter we show that a beam of R^- rotons can be created and detected. Since the R^- rotons travel ballistically, their interaction with the liquid surface can be studied and it is shown that quantum evaporation occurs with anomalous refraction. A preliminary attempt at this experiment has been previously reported.[1]

The elementary excitations in liquid ^{4}He are phonons and rotons which have the dispersion curve shown in Fig. 1.[2] The rotons may be divided into two groups, R^+ and R^- rotons which have, respectively, momentum parallel and antiparallel to their group velocities. If an excitation is incident on the free surface of the liquid He then it may be annihilated and an atom liberated into the space above the liquid. This quantum evaporation process has been demonstrated for phonons[3] and R^+ rotons[4] and is the best method for detecting high-energy phonons and rotons.

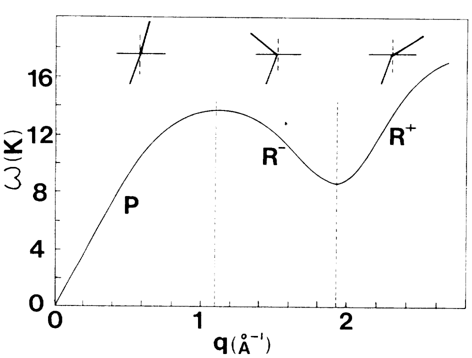

FIG. 1. The dispersion curve for phonons and rotons in liquid ^{4}He (Ref. 2) with the phonon P, R^- and R^+ roton regions defined. Inset: Typical quantum evaporation angles in the three regions.

Quantum evaporation by R^- rotons should give a very clear way of identifying these excitations as the atoms are liberated in the opposite quadrant to those evaporated by phonons and R^+ rotons. This is shown in Fig. 2 and stems directly from the boundary conditions of conservation of energy and the component of momentum parallel to the surface, i.e.,

$$\hbar\omega = E_B + mv^2/2\,, \tag{1}$$

$$q_{\parallel} = k_{\parallel}\,, \tag{2}$$

where $\hbar\omega$ is the energy of the excitation, E_B the binding energy ($E_B = 7.16$ K), m the mass, and v the velocity of the liberated atom. $q_{\parallel}$ and $k_{\parallel}$ are, respectively, the parallel components of momentum of the excitation and the atom. The anomalous refraction occurs because an R^- roton traveling towards the surface must have its momentum directed away from the surface.

Quantum evaporation by R^- rotons was not seen in the arrangement that successfully showed phonon and R^+ roton quantum evaporation.[4] This experiment employed a heater in the liquid to radiate excitation and a

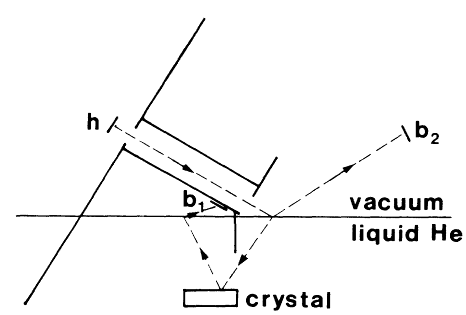

FIG. 2. The atom paths above the liquid and the R^- roton paths in the liquid are shown as dashed lines, together with the arrangement of the collimation and shields used in the experiment.

bolometer in the vapor to detect the evaporated atoms. It is possible to think of several reasons for this null result. For example, (i) the thin metal film heater which successfully creates phonons and R^+ rotons may not create R^- rotons, (ii) R^- rotons have a short lifetime, or (iii) that their probability for the evaporation process at the liquid surface is very low. The experiment described below uses a different way to create a beam of R^- rotons and its success indicates that the first of the above possibilities is correct. However, this raises the intriguing question: Why cannot R^- roton be injected by a heater in the liquid ^{4}He?

Besides showing that R^- rotons can be created and obey the boundary conditions given above, it is of interest to know the quantum efficiency P for the evaporation process. This is the probability that a roton incident on the liquid's surface evaporates an atom. The value of P impinges on three diverse subjects. The first is the proposal that the saturated vapor pressure of ^{4}He can be accounted for by a thermal distribution of excitations in the liquid quantum evaporating atoms into the vapor above it.[5] A dynamic balance is obtained by atoms condensing and creating excitations. An incident atom condenses with almost unit probability.[6,7] This implies values for P and so it is important to compare these with directly measured values. The second area is the damping of sheer waves in thin He films.[8] It has been suggested that this is due to quantum evaporation at the free surface and the value of P necessary for this model has been estimated. Third, it has been proposed that a neutrino detector can be designed using quantum evaporation by rotons.[9] The success of this proposal depends upon the quantum efficiency being reasonably high. We are able to make an estimate of P from our measurements.

We create R^- rotons by condensing He atoms onto the liquid-^{4}He surface. It has been shown[10] that condensation creates excitations in the liquid, possibly phonons and R^+ rotons. Furthermore, as the atom flux is reduced, the created excitation beam in the liquid travels at ballistic velocities.[11] The atom beam is produced by pulse heating a thin metal film which is covered with a thin layer of liquid He but is otherwise in a vacuum. The atoms are liberated in all directions and a beam is formed by collimation. Care is taken so that none of the uncollimated atoms reach the main liquid surface. The arrangement is shown in Fig. 2. The angle of incidence for the atom beam is large (58° to normal) so that few phonons can be produced.[5] This should maximize the production of rotons.

The detection of the R^- rotons cannot be done effectively with a bolometer in the liquid, and so the R^- rotons are reflected back to the liquid surface by a cleaved surface of NaF. At the liquid surface, atoms are evaporated and detected by a bolometer b_1 which is just above the liquid. The experiment is designed with shields to prevent atoms from the heater reaching the bolometer. Also, care is taken to avoid having any surfaces which could reflect R^+ rotons or phonons into the region where they might produce a signal. The reflecting crystal is positioned so that it only intersects R^- rotons. The measurements are made at temperatures $T \sim 0.1$ K where phonons and rotons can travel ballistically. The heater is pulsed for a time between 1 and 10 μs with a power from 0.5 to 5 mW/mm^2. The bolometer is used in a constant-temperature mode with the Zn superconductor on its transition edge at about half its normal resistance.[12,13] A magnetic field is applied to lower the transition temperature to ~ 0.3 K. The detected signal is amplified and then digitized with a Biomation 8100 transient recorder. Many signals were averaged in a purpose built fast averager to improve the signal-to-noise ratio. The signals are independent of pulse repetition rate which is typically 100 Hz for the heater powers used.

A typical low power signal is shown in Fig. 3(a) together with a modeled one in Fig. 3(b). The measured signal increases with heater power and peaks a little earlier as the heater power is increased. This is due to more atoms being evaporated at the heater and a shift of the atom spectrum to higher energies, which increases the velocity of the atoms and the R^- rotons created by them. Confirmation that the signal is from R^- rotons reflected from the crystal is obtained by replacing the crystal with another Zn bolometer (b_3). This bolometer showed no detected signal with 64 times the number of averages which typically produces good signal-to-noise results by the bolometer above the liquid with the crystal in place. This indicates directly that R^- rotons are not detected by a Zn bolometer in the liquid. Furthermore, when there is a bolometer at the crystal position the signal seen by bolometer b_1 is reduced in amplitude by at least a factor of 100. This indicates that the Zn bolome-

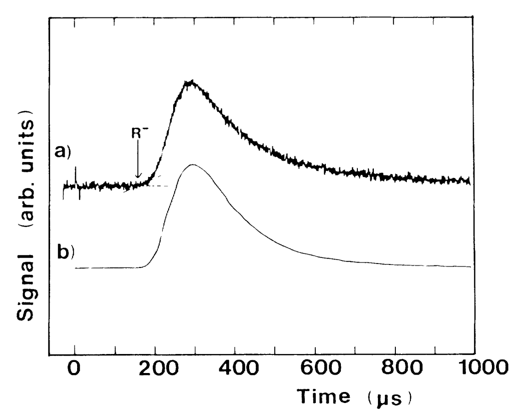

FIG. 3. (a) The measured R^- roton-atom signal is shown for 2-mW, 10-μs heater pulse. The arrow shows the calculated minimum arrival time for an atom-R^- roton event, corresponding to the R^- roton energy of 10.8 K. (b) The modeled signal for an atom beam with effective temperature 0.94 K creating a spectrum of rotons which propagate in the geometry of the experiment.

ter b_3 reflects rotons diffusely which is to be expected as the Zn surface is quite rough on the scale of the wavelength of the excitations.

In order to model the R^- roton signal it is necessary to know the spectrum of atoms arriving at the liquid surface. This is found by measuring the small fraction of atoms which are specularly reflected from the liquid surface with another bolometer, shown as b_2 in Fig. 2. Using the measured reflectivity function,[6] the atom spectrum condensing on the liquid surface can be found. To a good approximation it can be represented by a Boltzmann distribution at an effective temperature (e.g., $T_e=0.94$ K for a heater power 2 mW mm^2). The condensing atoms are assumed to create R^- rotons with a probability P_1. Using Eqs. (1) and (2) the energies and angles of propagation of the R^- rotons are calculated and then the rotons propagate ballistically to the crystal and further on to the liquid surface. The specular reflectivity of the crystal is R and is taken to be independent of excitation energy, as is P_1. The R^- rotons evaporate atoms with probability P_2. For the same angles and energy $P_1=P_2=P$ by time-reversal symmetry.

The geometry of the experiment, i.e., the sizes and positions of the heater, collimators, crystal, and bolometer, are included in a Monte Carlo calculation of the probability that an atom ejected by the heater causes an atom to be detected by the bolometer. The group velocity of the R^- rotons are found from the dispersion curve measured by inelastic neutron scattering.[2] The modeled signal shape is shown in Fig. 3(b) where it is seen to agree well with the measured signal. The correct prediction of the time for the fastest signal shown by the arrow in Fig. 3(a) is also strong evidence that we are dealing with R^- rotons. The behavior of the measured signal with heater power is also shown by the model.

To estimate the quantum efficiency (P) of evaporation by R^- rotons, we directly compare the R^- roton-atom signal to the reflected atom signal for the same heater power. This circumvents the approximation of describing the atom spectrum by an effective temperature. It is necessary to know the relative sensitivities of the two bolometers b_1 and b_2, the effect of the two experimental geometries, and to take into account the different temporal dispersion of the two signals.

The signal heights are compared at times which correspond to the same atom energy Ω in both measurements. The ratio of the signal heights S is given by

$$\left.\frac{S_{R^-}}{S_r}\right|_\Omega=\frac{P^2R}{r(\Omega)}\frac{\alpha_{R^-}}{\alpha_r}\frac{G_{R^-}(\Omega)}{G_r(\Omega)}\frac{D_r(\Omega)}{D_{R^-}(\Omega)},$$

where subscripts r and R^- refer to the reflected atom and R^- roton-atom experiments, respectively. $r(\Omega)$ is the atom reflectivity at the liquid surface and P and R are as defined previously. α_{R^-} and α_r are the sensitivities of the two bolometers. G_{R^-} and G_r are the respective probabilities for an atom of energy $\hbar\Omega$ which leaves the heater to get through the geometry, either as an R^- roton or an atom, and reach the respective detectors when $P=R=r=1$. D_r and D_{R^-} account for the temporal dispersion. Atoms leaving the heater in the energy range Ω to $\Omega+d\Omega$ at $t=0$ give rise to atoms arriving at the bolometers at times $t_{R^-}\to t_{R^-}+\delta t_{R^-}$ and $t_r\to t_r+\delta t_r$, respectively. The signal heights are measured at t_{R^-} and t_r but as $\delta t_{R^-}=\delta t_r$ the energy arriving at the bolometers corresponding to ejected atoms in the incremental energy range $\delta\Omega$ is proportional to $S_{R^-}(t_{R^-})\delta t_{R^-}$ and $S_r(t_r)\delta t_r$. Hence,

$$\frac{D_r(\Omega)}{D_{R^-}(\Omega)}=\frac{\delta t_r}{\delta t_{R^-}}=\left.\frac{dt_r}{d\Omega}\right|_\Omega\Big/\left.\frac{dt_{R^-}}{d\Omega}\right|_\Omega .$$

$dt/d\Omega$ is found graphically from $t(\Omega)$ curves, i.e., the ballistic arrival times as function of energy, which are calculated from the group velocities of the atoms and R^- rotons.

The relative bolometer sensitivities are found by interchanging b_1 and b_2 and repeating the measurements. The relative geometrical factors are found by Monte Carlo simulation of atoms and R^- rotons traveling through the geometries of the two experiments. Atoms are launched at the heater from random positions in random directions and their ballistic paths, together with those for the R^- rotons for the condensation experiment, tested to see if they get through the collimators.

From the above, we find $P^2R=0.2\pm0.02$. If we assume that R^- rotons ideally reflect from the cleaved crystal surface then $R=1$ and $P=0.45\pm0.1$. If $R<1$ then P is even larger. At the large angle of incidence used, 58°, we expect the atoms to condense with >0.99 probability[6] and mainly to create R^- and R^+ rotons. If they do this with equal probability then $p=0.5$. The measured value suggests that this is so, albeit within the considerable uncertainty in the measured value of P. We find that P does not show any marked dependence on the atom energy Ω at the angle used in the experiment.

This value of P is in broad agreement with other estimates. An average value of $P=\frac{1}{3}$ for all excitations was shown to account for the saturated vapor pressure of He, if it were due to quantum evaporation.[5] A value of $P=0.35\pm0.03$ for thermal rotons was found to account for the damping of shear waves in thin films of liquid He.[8] A recent estimate[14] from the diffuse atom reflection from thin He films gives an average roton $P\geq0.25$. The large value of P supports the proposal to use quantum evaporation in neutrino detectors, whether the rotons are produced in bulk He, or in thin He films on Si crystals. The fact that R^- rotons can specularly reflect with high probability from a cleaved crystal surface is also important for this proposal.

In conclusion, we have created a beam of R^- rotons by condensing atoms onto the surface of liquid ^{4}He. The R^- rotons are identified by quantum evaporation and the anomalous refraction that stems from the oppositely directed momentum and group velocity. The probability of evaporation by R^- rotons is estimated to be 0.45.

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