Scattering of ^{4}He Atoms Grazing the Liquid-^{4}He Surface

V. U. Nayak, D. O. Edwards, and N. Masuhara
Physics Department, The Ohio State University, Columbus, Ohio 43210
(Received 17 December 1982)

Measurements of the scattering of ^{4}He atoms grazing the surface of liquid ^{4}He show that the reflectivity approaches unity as the perpendicular wave vector tends to zero, in agreement with theoretical predictions.

PACS numbers: 79.20.Kz, 67.40.Fd, 68.10.Jy

This Letter describes an experiment on the scattering of free ^{4}He atoms striking the surface of the liquid. The reflection probability (or "reflectivity" R) of the atoms is measured as a function of their momentum $\hbar k$ and angle of incidence θ. In contrast with previous experiments[1,2] we have investigated the scattering when the de Broglie wavelength associated with the vertical motion of the atoms $2\pi/k_z$ is large compared with the characteristic lengths associated with the surface. These lengths are the interatomic spacing, which is roughly the same as the thickness of the surface, and λ the range of the van der Waals potential above the liquid, $-\alpha/z^3$. If the mass of the atom is m, then λ is given[1] by $2m\alpha/\hbar^2$. For ^{4}He, λ is 20 Å. In the short-wavelength regime, where $k_z\lambda > 1$, the earlier experiments showed that R is very small and that the dominant mode of scattering is absorption of the atom into the liquid.

If $k_z\lambda \ll 1$ the potential at the liquid surface should appear to the atom like a sharp attractive step. As $k_z \to 0$ the reflectivity should tend to unity, in agreement with the well-known quantum mechanical result for a step potential, provided that excitation of the liquid, i.e., inelastic processes, can be neglected. The experiment is carried out at low temperatures so that thermal excitation of the surface is unimportant. The experimental result shows that $R \to 1$ as $k_z \to 0$ and the detailed dependence of R on k_z follows the predictions of a theory [by Edwards and Fatouros[3] (EF)] which neglects inelastic processes completely. The EF theory has previously been used to calculate the binding of ^{3}He and spin-polarized hydrogen and deuterium to the ^{4}He surface, as well as to fit earlier data on scattering when $k_z\lambda > 1$. (Reviews of earlier work can be found in Refs. 2 and 4.)

The agreement between the experiment and the EF theory suggests that other current theories[5,6] overestimate the effect on R of the excitation of ripplons (quantized capillary waves) due to the van der Waals attraction between the incoming atom and the liquid. According to Echenique and Pendry[5] the attraction causes the multiple production of ripplons when the atom approaches within a few angstroms of the surface. They calculate R by a Feynman path integral restricted to a special class of trajectories. In Usagawa's theory[6] the same ideas are used but the coupling between the atom and the ripplons is assumed to be weak. This means that only single-ripplon production is considered, and the path-integral method is not needed.

In the EF theory[3] the atom moves in an effective potential $V_{\text{eff}}(z)$ which is asymptotic to the real potential $-\alpha/z^3$ at large distances above the liquid surface. The effective potential is derived by minimizing the energy of a variational wave function for the atom and the liquid. The wave function is not symmetrized with respect to the atom. With two adjustable constants, which determine the density profile of the liquid and the shape of $V_{\text{eff}}(z)$ near the surface, this is the only theory which fits the earlier experimental data. It predicts a distinct knee in R at $k_z \sim 0.03$ Å^{-1}.

The apparatus, illustrated in Fig. 1, is the same as that used earlier[1,7] with some modifications. The heater, T, is covered by the superfluid ^{4}He film. When a short heat pulse is applied, a beam containing 10^{14} to 10^{15} ^{4}He atoms is evaporated. The beam hits the surface of the liquid at ~0.02 K and can either condense or scatter off the surface. The screen, S, has a window which collimates the scattered beam. A bolometer, B, is used as detector. Both B and T are mounted on arms ~4 cm long which can be moved at low temperatures. The heating due to atoms condensing on B is measured for the direct beam and for the beam reflected off the liquid surface. The direct beam has a nearly Maxwellian distribution of velocities[2] with a temperature of ~0.6 K in this experiment. A comparison of the reflected and the direct power gives the reflection coefficient as a function of the time of flight and of the angle of incidence θ_1. When the scattering is elastic the time of flight gives the atomic velocity and the

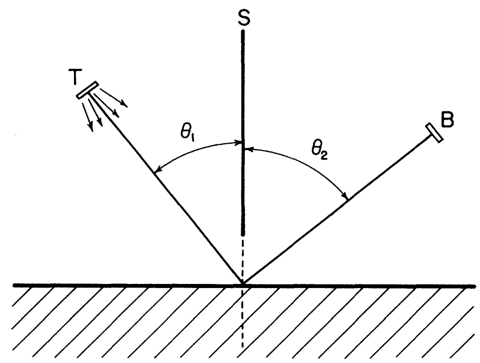

FIG. 1. Experimental arrangement (schematic). A heat pulse at T evaporates some of the ^{4}He film. The beam of evaporated atoms is collimated by the window in the screen S and detected by the bolometer B. The angles θ_1 and θ_2 are adjustable at low temperatures and the helium level can be raised so as to collimate the reflected beam more normally.

momentum $\hbar k$.

For the present work modifications were made to improve the angular resolution of the heater and bolometer. Both were cut from the resistance board used previously[7] and were 1.5×9.3 mm^2 as compared with 8×8 mm^2 in the original experiment. In addition the level of liquid in the cell was controlled so as to vary the effective window size (Fig. 1) to achieve narrow collimation of the reflected beam.

The improvement in the angular resolution of the bolometer was accompanied by two undesirable side effects. The signal-to-noise ratio was reduced by a factor of 2 to 3, but the more serious problem was a small signal due to the atomic beam heating the sides and terminals of the bolomter. This spurious signal arrived at the same time as atoms with $k \lesssim 0.2$ Å^{-1}, so that data in this range had to be discarded. In the original apparatus, because of the larger size of the bolometer, the effect was smaller and it occurred at a later time.

As in the previous experiment a search was made for inelastically scattered atoms outside the elastically scattered beam for which $\theta_2 = \theta_1 = \theta$. To our surprise a weak signal was found for angles of reflection larger than the angle of incidence, i.e., below the specularly reflected beam. In the previous experiment no such effect was observed and it was deduced that inelastic scattering was negligible. Further investigation showed that the nonspecular part of the signal was proportional to the square of the incident beam intensity (rather than linearly proportional to it),

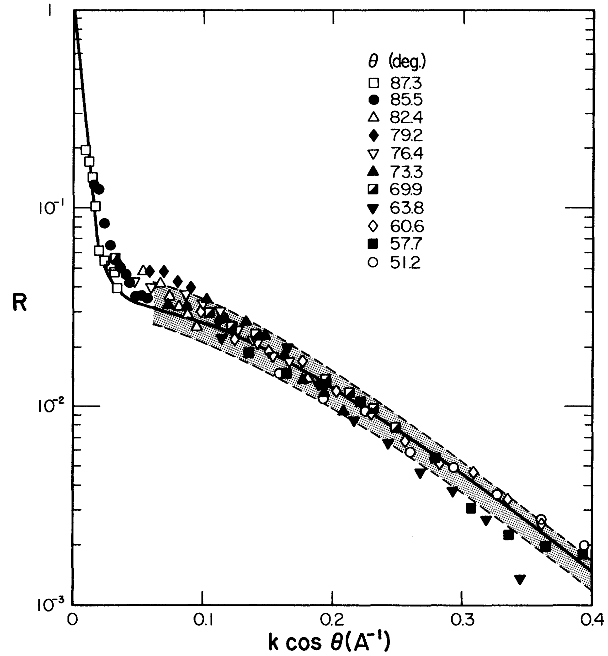

FIG. 2. Measurements of the reflectivity R as a function of k_z, the perpendicular wave vector of the atom. The data are compared with the EF theory (curve) and with the measurements of Ref. 1 which, if plotted, would lie between the dashed lines.

and that a small square-law component was also present in the supposedly specular part of the beam. Analysis of the data indicates that the effect is due to heating or excitation of the liquid surface by the earlier part of the beam which then affects the scattering of the later atoms. The data are not consistent with true inelastic scattering of individual atoms by the liquid in its ground state, since this would be proportional to the intensity of the incident beam. For large angles the surface heating was observed for all heat-pulse energies, from 0.07 to 0.95 erg. For the incident angles used in the original experiments, less than about 70°, the effect was found to be negligible.

To get rid of the nonspecular scattering due to heating all the data, i.e., measurements of the apparent reflectivity at a given angle and time of flight, were extrapolated to zero heat-pulse energy. After extrapolation there was no evidence for a genuine inelastic component in the scattering from the cold surface.

The extrapolated results are shown as a function of $k_z = k\cos\theta$ in Fig. 2 which compares them with the curve given by the EF theory. The earlier data,[1] taken for angles of incidence $\theta \leqslant 70°$, scatter close to this curve and between the dashed lines in the figure. It is clear that the new data are consistent with the old and, within the experimental error, with the theory. There is no evidence for any dependence on θ other than the simple dependence on k_z: $R(k, \theta) = R(k_z)$.

The new data agree with the prediction of the EF theory that there is a "knee" in $R(k_z)$ at about $k_z \sim 0.03$ Å^{-1}. Both the theory and the data approach $R(k_z) = 1$ roughly linearly as $k_z \to 0$. At very low k_z the reflectivity should have the form[8] $R = 1 - 4lk_z$ with l equal to ~ 75 Å for the EF potential.

It might be thought that the reflectivity at small k_z is sensitive only to the tail of the effective potential, i.e., the term $-\alpha/z^3$. That this is untrue can be demonstrated by varying the adjustable parameters[9] in the EF theory, $\gamma = -2.5$ and $\delta^2 = 8.5$ Å^2. These determine the shape of V_{eff} where it approaches its asymptotic value in the liquid, the ground-state energy per atom, $-L_4$. Changing γ and, to a lesser extent, δ^2 changes the position of the knee and the value of l quite strongly. The agreement between the new data and the EF curve tends to confirm the accuracy of V_{eff} in its most interesting region, close to the liquid surface.

It is instructive to compare the EF potential with a simpler one, the truncated van der Waals potential used by Usagawa. This has $V(z) = -\alpha/z^3$ for $z \geq z_0$; $V(z) = -L_4$ for $z \leq z_0$, where $z_0 = (\alpha/L_4)^{1/3}$. It gives a reflectivity $R(k_z)$ which differs considerably from the EF curve and from the data. It has a different slope near $k_z = 0$ (l is equal to 50 Å) and there is also a very deep minimum near $k_z \sim 0.07$ Å (see Fig. 1 in Ref. 6). The minimum is due to a resonance caused by the sharp change in the slope of $V(z)$ at $z = z_0$.

Although the EF potential gives good agreement with the experimental reflectivity, its theoretical significance is still unclear. This is because the variational wave function from which it is derived is not symmetrized with respect to the incoming atom and, more important, the possibility of excitation of the liquid has been completely neglected. EF have argued that the smoothness of the potential near the liquid surface imitates the effect of ripplon production in capturing the incoming atom, so that in this region V_{eff} has no real significance.[10] The agreement with the present data, and its sensitivity to the adjustable constants γ and δ^2, opposes this view, and supports the conclusion that ripplon production has a rather small effect on the reflectivity.

We would like to thank Mr. D. R. Swanson for his help during some of the experiments. The work was supported by Grant No. DMR7901073 from the National Science Foundation.

[1] D. O. Edwards, P. Fatouros, G. G. Ihas, P. Mrozinski, S. Y. Shen, F. M. Gasparini, and C. P. Tam, Phys. Rev. Lett. 34, 1153 (1975).

[2] D. O. Edwards and W. F. Saam, in *Progress in Low Temperature Physics*, edited by D. F. Brewer (North-Holland, Amsterdam, 1978), Vol. 7A, p. 285.

[3] D. O. Edwards and P. P. Fatouros, Phys. Rev. B 17, 2147 (1978).

[4] D. O. Edwards, Physica (Utrecht) 109B, 1531 (1982).

[5] P. M. Echenique and J. B. Pendry, Phys. Rev. Lett. 37, 561 (1976), and J. Phys. C 9, 3183 (1976).

[6] T. Usagawa, Phys. Lett. 73A, 339 (1979).

[7] Some experimental details can be found in D. O. Edwards, S. Y. Shen, J. R. Eckardt, P. P. Fatouros, and F. M. Gasparini, Phys. Rev. B 12, 892 (1975).

[8] The theory of "scattering of a slow particle" [L. D. Landau and E. M. Lifshitz, *Quantum Mechanics* (Pergamon, Oxford, 1977), Sec. 132] can easily be adapted to the one-dimensional problem of interest here.

[9] EF potential is given by $V_{\text{eff}}(z) = \hbar^2(a^{-1}d^2a/dz^2 - \beta^2)/2m$, where $a^2\rho_{\text{bulk}}$ is $\rho(z)$, the density profile, and

$$a = \{\exp[\beta z + \gamma + (\lambda/4\beta)/(z^2 + \delta^2)] + 1\}^{-1}$$

with $\hbar^2\beta^2/2m = L_4$.

[10] Note, however, that the EF potential and density profile give good results for the binding of ^{3}He to the ^{4}He surface (see Ref. 4) and that the binding is sensitive to the potential near the liquid.