Cold Collisions of Ground State ^{4}He: Giant S-Wave Scattering Cross Sections

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We have measured integral elastic cross sections for ground state ^{4}He-^{4}He scattering at collision energies from 1.35 to 0.5 K using a novel atomic beam apparatus built into a dilution refrigerator. Scattering is almost pure s wave, and is predicted to be enormous due to a possibly bound state near the continuum. The effective integral cross section ranges from 200 to 1000 Å^2 as collision energy is reduced in our experiment. These cross sections are in agreement with the values predicted using the latest analytical potential of Aziz and Slaman.

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The He-He ground state interatomic potential has attracted great interest from experimentalists and theorists alike for several decades. It is one of the weakest in nature and one of the most widely applied, as it is the starting point for microscopic calculations of bulk properties of liquid and solid ^{4}He, ^{3}He, and their mixtures, and of transport properties in ^{4}He and ^{3}He vapor. The latest and most sophisticated analytical potential, HFD-B2(HE), developed by Aziz and Slaman [1] is based on a fit to measurements of helium virial coefficients and viscosity [2,3] and *ab initio* calculations [4–6]. They have calculated that this potential supports exactly one bound state of ^{4}He-^{4}He with a binding energy of about 1.6522 mK (we calculate 1.728 mK), but the question of whether such a bound dimer state really exists remains an old experimental challenge. The Aziz-Slaman potential compares favorably with a recent *ab initio* calculation by Anderson, Traynot, and Boghosian [7]. Recently, Luo *et al.* [8] reported the first experimental observation of ^{4}He dimers in a supersonic expansion beam. It has been pointed out, though, that their data are consistent with the observation of ^{4}He trimers instead, and that there is still no real evidence for the existence of the ^{4}He dimer [9]. The presence or absence of a bound state depends crucially on the dimensions of the attractive well, and the most precise way to determine this part of the potential is by low energy scattering. In this Letter, we report low energy scattering cross section measurements made using an atomic beam scattering apparatus built into a dilution refrigerator. Gigantic cross sections which increase with decreasing scattering energy are observed, as expected for a potential with a possible bound state near the continuum. Our observed cross sections are in agreement with those predicted using the HFD-B2(HE) potential.

Previous measurements of scattering cross sections have been made at collision energies down to about 2.3 K for ^{4}He-^{4}He [10–12] and about 7 K for ^{3}He-^{3}He [12]. We note, however, that it is the s-wave contribution which grows at low energy, and none of these measurements were made in the pure s-wave scattering regime. Our measurements of the integral ^{4}He-^{4}He cross section were performed at collision energies from 1.35 K down to 0.5 K, corresponding to relative velocities from 105 to 65 m/s. Using calculations based on HFD-B2(HE), the scattering is over 93% s wave at the highest energies, increasing to 99.9% at the lowest. We observed effective cross sections increasing from 200 to 1000 Å^2 over our entire experimental range, as the collision energy was lowered. These measurements appear to support the latest potential and thus the existence of a bound state.

Our experiment is quite simple conceptually. An unattenuated, pulse beam of ^{4}He atoms is detected by a sensitive bolometer to give a time-of-flight (TOF) distribution, I_0. A ^{4}He target gas of known density, n, and temperature, T, is then introduced into the beam path, and the attenuated signal I_T is measured. One finds the transmission

$$S = I_T/I_0 = \exp[-L/\lambda_v(T)], \quad (1)$$

where L is the length of the scattering region, and $\lambda_v(T)$ is the mean free path for a beam atom with velocity v traveling through the target gas. We have taken λ_v to depend explicitly on T, since it is possible for the mean free path to change as the mean velocity of a target gas atom changes. The directly measured quantity is the effective cross section defined as

$$\sigma_{\text{eff}}(v,T) = 1/n\lambda_v(T). \quad (2)$$

There are several complications to this simple analysis, however, that we will discuss below.

Figure 1 shows a schematic of the experimental setup. The scattering chamber or cell is a 10 cm diam, 5 cm high copper can which is cooled by the mixing chamber of a dilution refrigerator. Enough ^{4}He is admitted into the cell to provide an essentially saturated film of superfluid ^{4}He covering all surfaces. The equilibrium vapor above the liquid helium film in the scattering chamber forms the target gas of ^{4}He. This density [13] is varied over many orders of magnitude from 6.6×10^7/cm^3 to 2.4×10^{13}/cm^3 by simply changing the temperature of the chamber from 250 to 430 mK. For our experimental conditions, the effective cross section depends very weakly on T in this range, so that varying T is a clean way of varying the target gas density and checking for consistent

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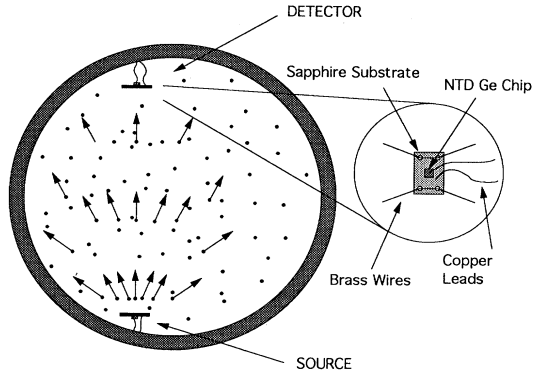

FIG. 1. Top view schematic of scattering chamber. The inset shows details of the NTD Ge composite detector bolometer. Sapphire provides a low heat capacity collection area for incident ^{4}He atoms.

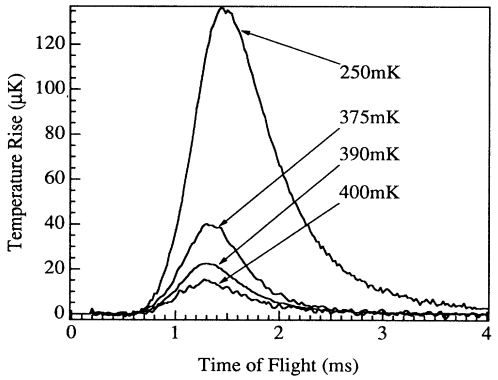

FIG. 2. Raw time-of-flight (TOF) data at various cell temperatures: 250, 375, 390, and 400 mK. Heater pulses were 25 μW and 60 μs long. Each curve is averaged approximately 1000 times.

results at different levels of beam attenuation.

A ^{4}He beam source and detector are positioned 8.3 cm apart, centered on the midplane of the chamber. The source and detector are identical resistive composite bolometers constructed from a $700\times700\times250$ μm^3 chip of neutron transmutation doped (NTD) germanium [14] glued to one side of a 1 cm$\times$1.5 cm$\times$50 μm plate of sapphire with silver-loaded epoxy. The inset in Fig. 1 shows a schematic of the detector bolometer. The bolometers are aligned towards each other and oriented so that each NTD Ge chip is on the back side of its sapphire plate, shielded from the other bolometer. The bolometers are suspended by several fine (12.5 μm) brass wires and by two 25 μm copper wires which also serve as electrical leads. The wires provide the paths by which superfluid ^{4}He can flow onto the bolometers and uniformly coat the surfaces. The construction techniques and performance characteristics of these bolometers have been described elsewhere [15,16].

In the operation of the source, the NTD Ge chip serves as a dissipative resistance and heats the sapphire during a short current pulse. ^{4}He atoms desorbed from the film on the sapphire during the pulse form the beam. The desorbing atoms have a thermal distribution of velocities which accounts for almost all of the 1 ms width of the TOF signal. We have found previously, though, that the beam's velocity distribution can narrow substantially due to scattering within the beam [17], the effect increasing with pulse power and with beam intensity. We chose to minimize this effect in order to have a wide range of beam velocities to analyze, so to this end we used relatively low power pulses, producing relatively low intensity beams [18]. For the scattering experiments here, the heater bolometer was given 60 μs long heat pulses at a repetition rate of 19 Hz. Data were taken for two different average pulse powers, 10 and 25 μW, which heated the sapphire and thus the desorbing ^{4}He atoms to roughly 430 and 460 mK, respectively.

The detector bolometer responds to arriving atoms from the beam by measuring their total deposited condensation energy, consisting of the heat of condensation (7.16 K) [19] and the kinetic energy ($\approx$ 1 K). The NTD Ge is current biased and the voltage drop across it is amplified and measured with a digital oscilloscope to record the TOF signal. When atoms condense on the sapphire, the entire bolometer heats, the NTD Ge resistance falls, and the voltage drop across it also falls. The signal is linear over the entire range of our measurements, so that the change in voltage drop is directly proportional to the power flux due to ^{4}He atoms condensing upon the detector. The detector signal was averaged for 50 s, giving a signal-to-noise ratio of over 50 for the unattenuated beam at a cell temperature of 250 mK. Changes in the flux hitting the detector of fewer than 2×10^8 atoms per pulse could be resolved at all cell temperatures below 400 mK. Above 400 mK, the ^{4}He target gas is too dense to make meaningful measurements in our geometry. The raw TOF data for the 25 μW heater pulses are shown in Fig. 2.

In order to obtain reliable quantitative cross sections a number of experimental conditions must be carefully controlled. The NTD germanium detectors are extremely sensitive and stable bolometers, but the detector sensitivity depends upon its temperature and the temperature difference from the thermal reservoir (cell walls). To minimize corrections to the detector sensitivity as the cell temperature was varied, the bias current (which determines the temperature of the bolometer) was adjusted to always operate the bolometer at the same temperature, 430 mK. The sensitivity or responsivity of the detector still changes with cell temperature due to the increased thermal coupling of the detector to the cell via the ^{4}He vapor. This was modeled, along with the formation of the beam by the heater, using numerical integration of the heat flow equations. All of the relevant parameters, the thermal couplings between the bolometer components and their heat capacities, were determined independently. All TOF data were renormalized according to the effective

detector sensitivity and beam intensity variations with cell temperature calculated by the simulation program.

The detector time constant at 430 mK is approximately 50 μs and independent of cell temperature, so that the TOF distributions have good temporal resolution. The signals, shown in Fig. 2, were divided up into four 100 μs windows and averaged to get a signal strength for each window. In this way, we were able to extract information at different beam velocities: 81.4 ± 4, 58.5 ± 2, 45.6 ± 1, and 37.4 ± 1 m/s. There is no measurable scattering below 300 mK, and accordingly we used the 250 mK data as our normalizing signal, I_0. The transmission S was calculated for each of the temperatures, T, for which TOF data were taken: 250, 375, 390, and 400 mK.

Because our beam is not a true collimated beam and the angle subtended by the detector is not small, it is necessary to correct for a number of distorting effects. One complication is that it is possible for beam atoms which scatter off of the target gas to still strike the detector. It is also possible for beam atoms which were not originally heading for the detector to be scattered into the detector. Both of these effects tend to reduce the measured cross section from its true value, and also to distort the dependence of cross section on beam velocity, since it is possible for a fast atom to be slowed considerably by a collision with a target atom and hit the detector inside of a different time window.

We have corrected for these effects with a Monte Carlo calculation, in which we keep track of three quantities: I_{free} is the flux of atoms that would hit the detector in the absence of collisions, I_{direct} is the flux of atoms that hit the detector without suffering a collision, and I_{hit} is the total flux of atoms that actually hit the detector, regardless of the trajectory. The scattering efficiency, ζ, is defined as $(I_{\text{free}} - I_{\text{hit}})/(I_{\text{free}} - I_{\text{direct}})$ and is a measure of the average number of beam atoms deflected from the detector per collision. We find that ζ falls between 75% and 85%, and that it depends weakly upon target gas temperature, beam atom velocity, and mean free path. The transmissions were then corrected for this effect by replacing S (which in the ideal case should equal $I_{\text{dir}}/I_{\text{free}}$) by $1-(1-S)/\zeta$. Using Eqs. (1) and (2), a cross section at each cell temperature, T, and each beam velocity, v, was calculated.

A potential complication arises due to scattering within the beam itself. Intrabeam scattering can result in a distortion of the TOF signal and also could lead to scattering efficiencies greater than 1 as the deflected beam atom could scatter other beam atoms out of the path to the detector. We have analyzed the effects of intrabeam scattering with another Monte Carlo simulation and have found that the overall correction in our case is negligible. Experimentally, this is confirmed by the lower heater power data which give identical results, even though the beam density is roughly a factor of 2 lower.

One further complication arises because ^{4}He atoms are constantly desorbing from the detector which is heated above ambient temperature. These atoms can scatter beam atoms and contribute to the total attenuation. However, for a cell temperature greater than about 370 mK, our simulations show that the film on the detector sapphire substrate remains very close to the cell temperature. Additionally, the effect becomes very small at higher cell temperature because the total beam attenuation is much larger and the contribution from desorbing atoms is tiny by comparison. We have included only the 375, 390, and 400 mK data in our analysis, so that no correction is needed.

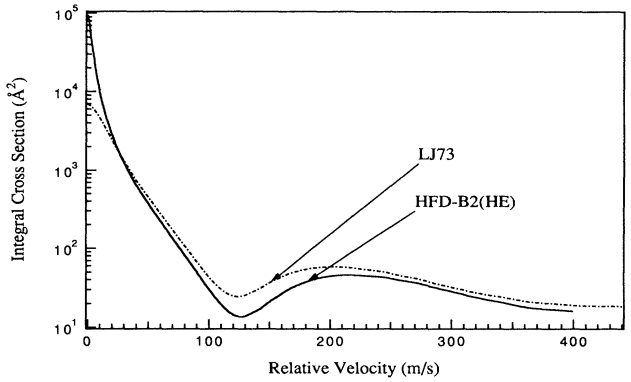

FIG. 3. Integral cross section, $\sigma(g)$, versus collisional relative velocity calculated using the ^{4}He-^{4}He HFD-B2(HE) potential. Also shown are calculations based on the semiempirical Lennard-Jones potential (LJ73) of Ref. [21].

The theoretical effective cross section $\sigma_{\text{eff}}(v,T)$ defined in Eq. (2) for our experimental situation is related directly to the theoretical integral cross section $\sigma(g)$ by the convolution integral [20]

$$\sigma_{\text{eff}}(v,T) = 2\int_0^\infty \int_{-1}^{1} \sigma(g)(g/v)\frac{2}{\sqrt{\pi}\alpha^3} v_{\text{targ}}^2 \times \exp(-v_{\text{targ}}^2/\alpha^2) dv_{\text{targ}} d\mu , \quad (3)$$

where v_{targ} is the speed of a target gas atom, $\alpha = (2k_B T/m)^{1/2}$, m is the mass of a ^{4}He atom, μ is the cosine of the angle between the velocities of the beam atom and target gas atom, and g is the relative speed of the beam atom to a target gas atom, given by

$$g(v^2 + v_{\text{targ}}^2 - 2vv_{\text{targ}}\mu)^{1/2} . \quad (4)$$

The integral cross section is a function of relative velocity and is determined by the interaction potential. It is plotted for the HFD-B2(HE) potential in Fig. 3 along with the same quantity calculated from an older Lennard-Jones type He-He interatomic potential (LJ73) [21]. The factor of 2 outside the integral in Eq. (3) arises from the fact that the ^{4}He atoms are indistinguishable bosons.

The experimental cross sections were extracted from the 25 μW pulse power data, but the 10 μW pulse power data gave identical results to within 5%. Since the experimental effective cross sections $\sigma_{\text{eff}}(v,T)$ are rather in-

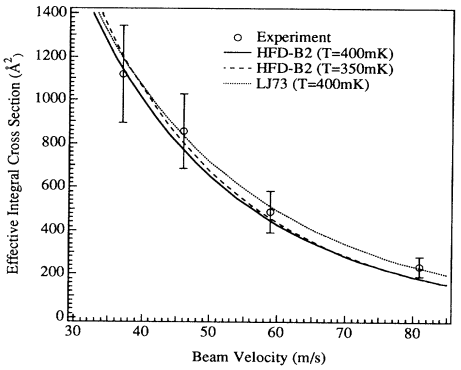

FIG. 4. The data shown with the effective cross sections calculated from Eq. (3) and the two potentials HFD-B2(HE) and LJ73. The data at each cell temperature (i.e., target gas density) have been combined into one averaged data point for each beam velocity. The dominant contribution to the error bars is systematic error.

sensitive to T for our range of v and T, we have combined the cross section measured at each cell temperature into a single average cross section for each given beam velocity. We show these data, σ_{eff} versus v_{beam}, in Fig. 4, along with the predictions of HFD-BD(HE) and LJ73 calculated from the cross section in Fig. 3, using Eq. (3). The error bars shown are predominantly due to systematic error. The main source of error lies in our absolute temperature calibration, which is only good to ± 3 mK. This leads directly to error in the target gas density and thus in the extracted cross section. Another source of error is in our calculation of the efficiency correlations (ζ).

The experimental data lie near the predicted effective cross sections and have the same steep dependence upon relative velocity or collision energy. Observation of such giant integral cross sections is strong evidence that the ^{4}He-^{4}He system is either just bound or just barely unbound [22]; however, our results do not directly answer the question of the existence of a dimer state of helium. Indirectly, of course, our measurements support the existence of the helium dimer insofar as they are in agreement with HFD-B2(HE). The LJ73 potential also has a bound state, although a much deeper one of about 32 mK, and an s-wave scattering length $a_s = 23$ Å. These two potentials would easily be distinguished at still lower collision energies than accessed here, as the HFD-B2(HE) potential has $a_s = 87.5$ Å. We note that because of the accidental tuning of this potential, integral cross sections at low energies are extremely sensitive to small changes in various parameters, including the reduced mass of the well depth [23].

The low temperature technique we have presented here opens the way to studying ultracold collisions of light, weakly interacting atoms in their ground states. Extending these techniques to ^{3}He-^{3}He and ^{3}He-^{4}He scattering will help to determine the He-He potential to a higher degree of precision.

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