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A micromechanical detector for molecular beams

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We demonstrate the detection of a molecular beam by means of a micromechanical momentum transfer detector operated in vibrational resonance. With a sensitive surface area of $0.5\times 0.3\,\text{mm}^2$ the small paddle allows us to detect a beam with 6.5×10^7 He atoms hitting the surface per second. The detector response time equals the damping time of the paddle oscillation of about 1 s. The detector is sensitive enough to measure intensities in molecular beam scattering experiments. The novel detection scheme has the potential to allow the development of a position sensitive molecular beam detector. © *1999 American Institute of Physics.* [S0034-6748(99)01709-8]

I. INTRODUCTION

The efficient detection of neutral chemically inert beams remains a challenge in experimental physics. Noble gas beams, especially He beams, have important applications, for example, in surface science where they play a role as probe particles comparable to the role of neutrons in solid state physics. They allow, e.g., surface phonon spectroscopy and the nondestructive study of weakly adsorbed molecules on surfaces.[1,2] The most versatile detector with a satisfactory performance for thermal molecular beams is the electron-bombardment ionization detector, a commercially available standard vacuum instrument. Even with improved ion optics its counting efficiency is, however, only around 10^{-5} for ground state neutral He beams.[3] With this low efficiency in mind one feels challenged to search for better detection methods. After recent progresses in micromechanics one may suppose that the force exerted by a molecular beam may be large enough to be measurable with a micromechanical device. In order to discuss the applicability of the idea we define the weakest detectable He molecular beam in present experimental setups by the intensity equivalent to the background counting rate. With a background signal of 50 counts/s in a He ionization detector in an ultrahigh-vacuum (UHV) chamber this limit becomes 5×10^6 He atoms/s. Note that this very low intensity corresponds to only 10^{-5} of the primary He beam intensity obtained from modern nozzle beam sources. At a thermal velocity of 1800 m/s (66 meV kinetic energy) the momentum of each He atom is $1.2\times 10^{-23}\,\text{N s}$. The momentum transferred to a surface from which the beam is diffusely reflected is larger by a factor of 5/3. A beam at the detection limit in a He scattering apparatus thus exerts a force of only $10^{-16}\,\text{N}$. However, recent publications report on force detection down to the aN ($10^{-18}\,\text{N}$) range.[4,5] Thus molecular beams may well be detectable by extremely sensitive force detectors. One has to consider, however, that force detectors may have extremely small dimensions, while a beam detector must possess a much larger surface in order to be hit by a sufficiently large molecular flux.

In this article we present the application of a micromechanical device to the detection of a thermal molecular beam. The detector consists of a metal paddle $300\,\mu\text{m}\times 500\,\mu\text{m}$ held by two lever arms on a ground plate. A vibration is excited by a pulsed He beam at the lowest resonance frequency of the detector. The vibrational amplitude is monitored by a laser beam reflected from the paddle. We find an experimental detection limit of 6.5×10^7 He atoms/s.

The cantilever was originally designed as a laser beam scanner and is micromachined based on silicon and thin film technology. Improvement of the design with respect to the requirements of the molecular beam detector can lead to well suited and sensitive neutral beam detectors with decisive advantages. The new detector type is insensitive to diffuse background gas as molecules impinging continuously or isotropically do not excite the resonant motion of the lever. The detector can thus be operated without differential pumping stages which make He scattering devices to date expensive. It can be employed even at high background pressures of reactive gases where detectors based on hot cathodes, for example, would fail. As the directional information of the He beam is used, no mass selection is required. The size of the complete detection unit is determined by the technique employed to read out the levers vibrational amplitude. For laser beam deflection it has dimensions of a few cm. Amplitude detection by capacity measurement, e.g., may reduce the size to below 1 mm^2. Such a device may allow us to fabricate a detector array which can serve as a position sensitive detector recording a complete angular intensity distribution in a molecular beam experiment simultaneously.

II. DESIGN

We used a paddle cantilever design developed for an optical bar-code scanner[6,7] [Fig. 1(b)]. It consists of a rigid Cu plate 300 μm by 500 μm and 8 μm thick held by two

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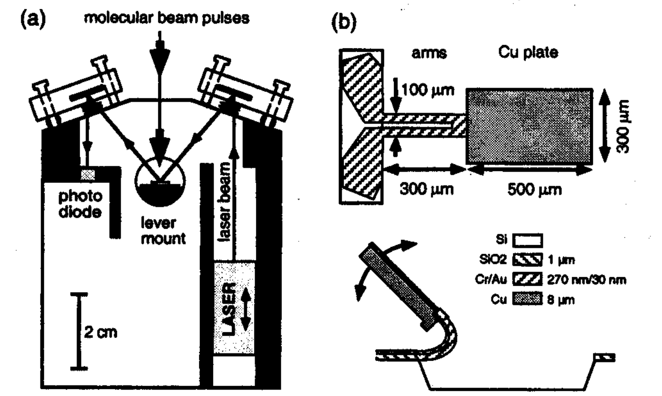

FIG. 1. Schematic of the micromechanical paddle detector: (a) base plate and beam deflection geometry for vibrational amplitude readout, (b) geometry and layer composition of the paddle cantilever; (top) planar dimensions; (bottom) bent geometry controlled by the relaxation of stress in the bimorphic structure of its arms.

bimorphic arms which are thin and narrow, allowing the Cu plate to make a hindered rotation around an axis not far from its edge. Excitation of the lowest resonance mode by a pulsed, homogeneous force on the paddle leads to a combination of paddle displacement and paddle rotation determined by the paddles substantial moment of inertia. The layered design of the arms [Fig. 1(b), bottom] leads to a temperature dependent position of the paddle which results in our application in an unwanted drift of the reflected laser beam when vacuum is established. Also the large mass of the Cu paddle is disadvantageous as will be discussed later. Its proper frequency around 300 Hz is, however, high enough for the application and lies in the frequency range accessible to the pulsed nozzle source.

The rotational amplitude of the paddle is measured by the laser beam deflection method in which the paddle angle is detected by the displacement of a reflected laser beam on a four-quadrant photodiode. The setup consists [Fig. 1(a)] of a diode laser assembly, two adjustable mirrors, and a four quadrant photodiode (Hamamatsu S1651-03). The high vacuum compatible diode laser assembly (supplier: Schäfter&Kirchhoff, Hamburg) contains a diode laser (Hitachi HL6712G), a collimator, a pinhole, and a focusing lens ($f = 88$ mm). The assembly can be moved along a channel in the base plate which is parallel to the beam direction so that the position of the focus can be moved between the cantilever and the photodiode in order to select the highest detection sensitivity. The first Au mirror allows us to position the laser beam on the cantilever paddle, and the reflected beam is centered on the photodiode by means of the second mirror. The cantilever is fixed on a mount which can only be coarsely adjusted. External vibrations are passively damped by mounting the whole assembly of Fig. 1(a) on a stack of five Cu plates separated by viton rings (resonance frequency around 50 Hz), an efficient technique commonly employed in scanning probe microscopy.

The position of the reflected beam on the quadrant diode is assessed by subtracting the photocurrents from two halves of the diode sensitive area. The electronics for amplification and subtraction of the four-quadrant photodiode signal was originally developed for a laser beam deflection atomic force microscope.[8] The electronic circuits were used without modification.

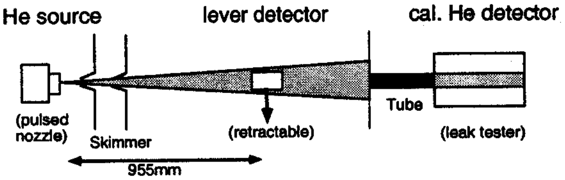

FIG. 2. Experimental setup. The beam generated by the pulsed nozzle source is measured by the paddle detector (Fig. 1). Alternatively, the detector is moved out of the beam to determine the absolute molecular flux in a calibrated He detector (UHV leak detector).

III. EXPERIMENTAL RESULTS

The experimental setup is schematically shown in Fig. 2. The momentum transfer detector is mounted in a high vacuum (HV) chamber (10^{-7} mbar). The cantilever is excited at resonance by a He beam generated by a pulsed nozzle source (Lasertechnics Inc., Albuquerque, Model LPV). The beam is collimated by two skimmers. The source parameters in the experiment are: stagnation pressure 5 bar, temperature 320 K, nominal nozzle diameter 0.3 mm, and nominal pulse width 43 μs at a repetition frequency near 310 Hz. The source has been described and characterized earlier.[9,10] When the momentum transfer detector is moved out of the beam, the forward flux from the nozzle can be measured directly by a calibrated He leak detector. The averaged He flux can be directly calculated from the indicated leak rate. The leak detector and the HV system are coupled by a 300 mm long tube (4 mm diameter) in order to separate the two vacuum systems while allowing the directed beam to pass unhindered. For the nozzle parameters given above a mean intensity in a pulse of $3.1 \times 10^{19}\,\mathrm{s^{-1}\,sr^{-1}}$ is obtained, in good agreement with literature values of nozzle beam sources.[10,11] We then know that 2.1×10^8 atoms hit the cantilever surface during each pulse.

Figure 3 shows the measured resonance curve (dots) of the paddle cantilever excited by the He pulses. A good fit (solid line) of the data points requires the sum of two Lorentzians: The narrow Lorentzian [0.43 Hz full width half maximum (FWHM)] corresponds to the bending motion of the paddle and the strongly damped Lorentzian (3.7 Hz FWHM) might be due to coupling to other vibrational modes of the cantilever. The fit gives a resonance frequency of 309.8 Hz with a quality factor (Q factor) of 1110 compared to 72 measured in air. The vibrational amplitude in Fig. 3 is obtained from the voltage output of the differential amplifier after calibration with a known static deflection angle.

The noise equivalent amplitude for 1 Hz bandwidth at room temperature is 1.2 μrad. This value can be completely attributed to the thermomechanical noise of the cantilever. As we obtain a maximum resonance amplitude of 1.15 mrad in Fig. 3 a beam intensity three orders of magnitude smaller can thus still be detected. The smallest detectable pulse contains 2.1×10^5 atoms from which we obtain (310 Hz) the noise equivalent intensity of $6.5 \times 10^7\,\mathrm{s^{-1}}$.

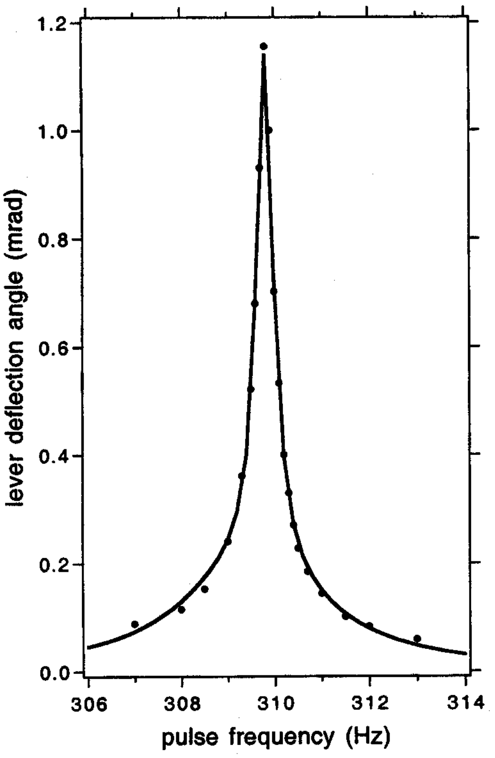

FIG. 3. Cantilever resonance curve (dots) recorded by tuning the repetition rate of the pulsed molecular beam. The solid line is a fit.

From four tested paddle detectors, three exhibited parameters which were very similar to those given above; the fourth had a Q factor which was smaller by a factor of 2. Signal and noise traces of a second lever ($\nu=278\,\mathrm{Hz}$, $Q=1300$) are shown in Fig. 4 together with the corresponding frequency spectrum. The peak width of the detector resonance is entirely due to the cutoff in the time domain of the oscilloscope traces.

For comparison of the detection efficiency of a pulsed beam with a continuous beam we remark that a beam chopper with 50% duty cycle can provide pulses resonant with the detecting cantilever at the sacrifice of 50% of the beam intensity. A beam with 50% duty cycle has an efficiency of $2/\pi$ in resonant momentum transfer compared to an infinitely short pulse with the same momentum transfer. Chopping of a continuous beam can thus still exploit $1/\pi$ of its total momentum transfer in a resonant setup. Thus the noise equivalent intensity of $6.5\times 10^7\,\mathrm{s}^{-1}$ could be provided by a continuous beam with an intensity of $2\times 10^8\,\mathrm{s}^{-1}$ chopped at the paddle resonance frequency.

The response time (or inverse time resolution) of the paddle detector is given by the decay time of the free paddle vibration

$$\tau=Q/(\nu^*\pi)$$

in agreement with the experimental value of $\tau=1.5\,\mathrm{s}$ measured for a paddle with a Q factor of 1300 and a frequency of 278 Hz.

IV. DISCUSSION AND OUTLOOK

The setup presented here exhibits a detection limit (1 Hz bandwidth) less than 2 orders of magnitude above the background counting rate of a He ionization detector. This is an excellent result if we take into account that the employed cantilever was not optimized for this application. The experimental problems of the present setup are twofold: (1) The

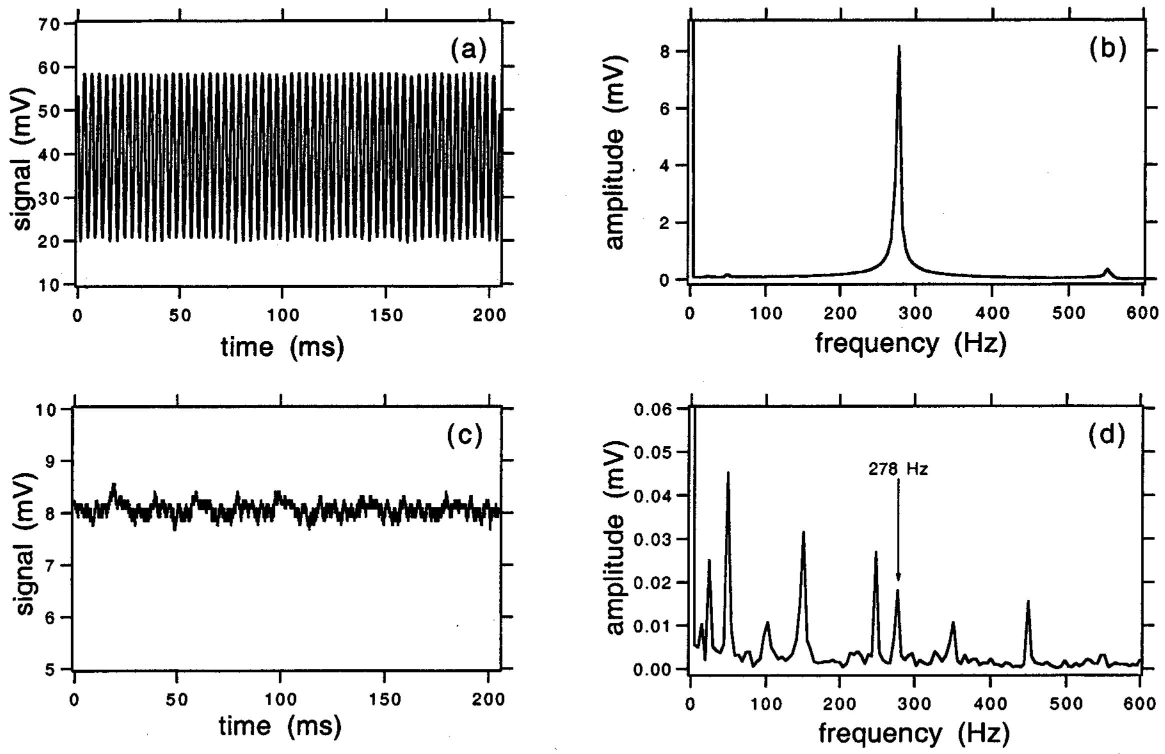

FIG. 4. Traces of the signal (a), (c) from the output of the amplifier unit and their Fourier transforms (b), (d). With the He beam exciting the cantilever at resonance (a), (b) and without He beam (c), (d). The cantilever frequency was 278 Hz in contrast to the lever used in Fig. 3 ($\nu=310\,\mathrm{Hz}$).

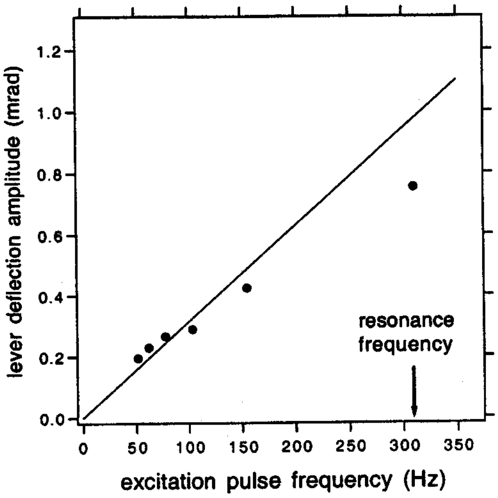

FIG. 5. Apparent paddle deflection amplitude for a series of nozzle frequencies which excite the paddle in every, every second, every third,... oscillation. The deviation from linearity is largely due to beam attenuation by background gas collision which appears at higher pulse repetition rates, i.e., higher gas fluxes.

resonance frequency of the lever changes in vacuum probably due to desorption from the lever. The observed shift by $+0.5$ Hz (0.2%) for 2 days is substantial with respect to the width of the resonance curve. Some means must be provided in a future application to adjust the resonance frequency, especially if an array of identical detectors shall be employed. (2) The peak at the second harmonic (556 Hz) of the resonance frequency in Fig. 4(b) is due to deviations from linearity in the detection of the laser beam deflection. This indicates that the reflected laser beam is no more centered on the photodiode and/or the shape of the reflected beam is distorted. The deadjustment of the laser beam by the temperature dependent bending of the two arms can not be compensated in vacuum at present. *In situ* adjustment of the mirrors in vacuum appears necessary. While a well adjusted deflection detector will exhibit a linear relation between beam intensity and laser deflection, some nonlinearity may occur in the present case. Figure 5 shows the apparent paddle deflection angle calculated from the diode signal for He pulse repetition rates tuned to lower harmonics (1/2, 1/3, 1/4,...) of the paddle resonance frequency. Part of the deviation from linearity, however, is due to pulse attenuation by the background gas.

Calculations based on the material constants in an oversimplified model (both arms and paddle are assumed to have Cu mass density and SiO_2 elastic constant) with the actual dimensions of the paddle cantilever yield a realistic bending frequency of 313.5 Hz. In the model a cantilever deformation amplitude of 1.2 mrad results from short force pulses of $1.4\times10^{-14}\,\mathrm{N\,s}$ ($Q=1000$) in reasonable agreement with the beam characteristics. The force constant of the lever is estimated to be not smaller than 0.07 N/m. Parameters to be improved according to an analysis based on finite element simulations and analytical calculations[12] are the following: The force constant of the paddle cantilever shall be small. However, it must provide a high resonance frequency (above 1 kHz) which reduces thermal and acoustic noise and also assures mechanical stability with respect to strong dc accelerations like, e.g., the earth's gravitation. In addition, for a given Q factor the detector response time reduces when the resonance frequency is increased. A small force constant and a high frequency imply a low paddle mass and thus small dimensions as well as a minimal thickness which is limited, however, by the requirement of paddle rigidity. The mass can be reduced also by the use of a light material, e.g., Si instead of Cu. The Q factor, finally, may be substantially increased by using monocrystalline Si.[5] The loss of molecular flux in a molecular beam experiment with smaller cantilever dimensions can be compensated by mounting the detector closer to the sample from which the He beam is scattered. This improvement is, however, strongly limited because the finite diameter of the beam will reduce the angular resolution.[13] An optimized design was estimated to have a 50 times higher signal to noise ratio than the design presented here.

The properties of different cantilever geometries have been simulated and no substantial differences in efficiency have been found when the material parameters, the sensitive area, and resonance frequency remain fixed. Especially, designs with lowest frequency modes in which the arms holding the paddle are deformed either in bending or in torsion provide rather comparable signal to noise ratios.

We demonstrated that it is possible to detect even weak molecular He beams by their momentum transfer to a micromechanical paddle cantilever. The detectors sensitive surface is $0.5\times0.3\,\mathrm{mm}^2$ and it allows us to detect pulsed beams of 6.5×10^7 He atoms/s which can be obtained by chopping a beam of 2×10^8 He atoms/s with 50% duty cycle. The response time of the detector is around 1 s. Fabrication from single crystalline Si with a smaller sensitive surface and a higher vibrational frequency is expected to improve its performance, making the detector efficient enough for molecular beam scattering experiments. The micromechanical paddle cantilever opens up the possibility of developing versatile position sensitive molecular beam detectors.

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