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RESEARCH PAPERS

A pulsed molecular beam source

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Abstract A rapid acting gas valve is described. The opening and closing motions of the valve are under separate electrical control and the opening time of the valve can be varied over the range 10 to 100 μs. At moderate opening times, 20–30 μs, the valve produces high intensity pulsed beams (1×10^{22} atoms/sr/s) of various molecular species with narrow velocity distributions ($\Delta v/v$ typically 7%).

1 Introduction

The principal element in a pulsed molecular beam source is a fast gas valve acting between a high pressure reservoir and an evacuated chamber. Normally the valve is closed so that the reservoir and vacuum chamber are isolated from each other. During its short opening time the valve allows gas from the reservoir to flow through a nozzle and expand into the vacuum. A free expansion is ensured by having a valve opening time less than the beam flight time across the vacuum chamber. The pulse of expanding gas is collimated and, as with a conventional nozzle beam (Anderson 1974), the hydrodynamic expansion through the nozzle leads to a narrowing of the beam velocity distribution.

In continuous molecular beam sources the beam intensity is limited by the size and capacity of the associated vacuum pumps. Thus, a high intensity source is necessarily a large piece of equipment. Also, the constant gas load applied to the system by a continuous beam leads to an unwanted background signal at the detector that limits the experimental sensitivity. Pulsed sources offer a number of advantages in these respects. Their size is very much smaller yet they can achieve substantially higher peak intensities than those obtained from most continuous beam sources. With a pulsed beam it is also possible to reduce the background signals at the detector by any required degree, simply by reducing the pulse repetition rate. The system then has time to pump away background gas between pulses.

The price paid for these advantages lies in the greatly reduced duty cycle of the pulsed beam. In many cases, however, this is not a disadvantage since the pulsed nature of the source is ideally suited to inelastic scattering experiments and time of flight measurements.

A number of pulsed valve designs have been proposed (see Bassi *et al* 1981, for references) but few are capable of generating the short pulses required in high resolution inelastic scattering studies. Short pulse durations have been obtained with the design of Gentry and Giese (1978) where the valve opening was determined primarily by the vibrational properties of a stiff metal bar. In the design described below we have sought to eliminate this reliance on mechanical properties and have succeeded in developing a valve where both opening time and opening amplitude can be adjusted electrically.

The advantage of our approach can be seen from a consideration of the factors that determine the characteristics of a pulsed molecular beam. The most important experimental parameter is the time spreading of a single beam pulse, measured at the beam detector. It is usually desirable to minimise this spreading. Two factors contribute to the time spread: first the valve opening time and second the distribution of velocities present in the beam. Gentry and Giese (1978) point out that with very short valve opening times (≈ 10 μs) there is insufficient time for the hydrodynamic flow through the nozzle to become fully developed. In consequence the velocity distribution in the beam is somewhat broader than would be expected from a continuous nozzle beam operating under similar conditions. On the other hand, Liverman *et al* (1978) present evidence for very narrow velocity distributions in pulsed beams where the valve opening time is greater than 100 μs. For a detector close to the source small opening times are more important than a narrow beam velocity distribution; with a more distant detector it may be advantageous to work with somewhat longer valve opening times and benefit from the consequent narrowing of the beam velocity distribution. Different gases require different operating conditions and an important feature of the present design is the ability to optimise the performance for any gas by varying the valve opening time so as to minimise the spread of the arrival times at the detector.

The valve has been used successfully in studies of the inelastic scattering of molecules from solid surfaces (Allison and Feuerbacher 1980).

2 Description

A scale drawing of the valve is shown in figure 1. This is a view of the valve in cross section, the section being taken through the

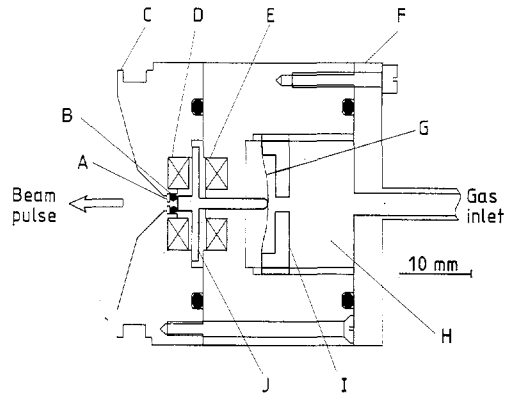

Figure 1 Scale drawing of the valve in cross-section. (A) nozzle; (B), O-ring seal; (C), valve body–Delrin; (D), opening coil; (E), closing coil; (F), rear valve body and gas inlet-stainless steel; (G), leaf spring–carbon fibre; (H), gas reservoir, free flow of gas between the rear and front of the valve is ensured by a series of longitudinal channels, not shown in this view; (I), spring tensioner; (J), aluminium valve stem.

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axis of cylindrical symmetry, coincident with the beam axis. The valve seal is made between a viton O ring (B) and the aluminium valve stem (J). The action of a light carbon fibre leaf spring (G) maintains the seal against the vacuum. Motion to open and close the valve is produced by passing currents through the coils D and E. A pulsed current in coil D produces a rapidly changing magnetic field along the axis of the valve. The changing field induces counter-circulating currents in the valve stem (J) that gives rise to a strong repulsive force between the stem and the coil. As the stem moves away from the coil (D) the seal to the vacuum is broken and gas from the reservoir (H) flows through the nozzle (A) into the chamber. The motion of the stem is reversed when a pulsed current is applied to coil E. On its return, the stem collides inelastically with its seat and the vacuum seal is reformed as the stem comes to rest. Excessive stress on the O ring is minimised by arranging for the valve stem to seat around its periphery, as shown in figure 1.

The current pulses required to open and close the valve were obtained by discharging low inductance capacitors (20 μF) through each of the coils, using spark-gap switches (EGG, GP 82-B). The valve opening time is determined primarily by the time delay between the opening and closing current pulses. Typical charging voltages for the capacitors were in the range 1000–1400 V. Once triggered, the electrical circuit consisting of capacitor, coil, spark-gap and connecting wire behaves like a damped resonant circuit. The damping arises from two sources. First, the spark-gaps and wiring have an intrinsic series resistance in which power is dissipated. Secondly, the valve stem itself tends to damp the circuit as it gains kinetic energy at the expense of the electrical energy in the resonant circuit. This damping is insufficient to prevent the circuit ringing. To reduce the amplitude of the ringing and increase the life expectancy of the spark-gaps an additional series resistance is included in each circuit. The resistances are made from strips of stainless steel 0.5 mm thick, 5 mm wide and approximately 60 mm long; typical resistances are a few tenths of an ohm.

The coils (D, E, figure 1) are constructed from thin strips of OFHC copper (width 3 mm, thickness 0.1 mm). Each is spirally wound on a flat form with nine turns of gradually increasing radius.

A number of different nozzle sizes were tried, ranging from 0.1 to 0.8 mm. As the nozzle diameter is increased the beam velocity distribution narrows for a given stagnation pressure (Anderson *et al* 1966); however, the rise and fall times of the beam pulse are degraded by a large nozzle diameter. The final choice, 0.5 mm, was a compromise between these factors.

3 Performance

Measurements of the valve performance were carried out with the valve mounted on to a UHV scattering chamber that had two radial flight tubes. Detectors for a time of flight analysis of the beam intensity were incorporated in each flight tube. One of the tubes was positioned to accept atoms scattered from a crystal surface located centrally in the UHV chamber, while the other was arranged directly in line with the source and provided a measurement of the molecular beam when the scattering surface was retracted. A beam collimator (diameter 3 mm) was located close to the crystal surface, approximately 180 mm from the source. The main scattering chamber was pumped by an ion pump (220 l s^{-1}) combined with a turbomolecular pump (200 l s^{-1}) and titanium sublimator. The flight tubes were evacuated by an additional turbomolecular pump with an effective pumping capacity of about 50 l s^{-1}. The beam detectors were commercial UHV Bayard–Alpert ion gauges and the ion currents measured with fast electrometer amplifiers. A voltage to frequency converter transformed the amplifier output voltage into a pulse train that was fed directly into a multichannel analyser operating in the multi-scaling mode. The channel width of the multichannel analyser was 10 μs.

With a pulsed helium beam expanding from a reservoir at 2.5 MPa (25 bar) the signals obtained at two ion gauge detectors in the direct flight tube are shown in figure 2.

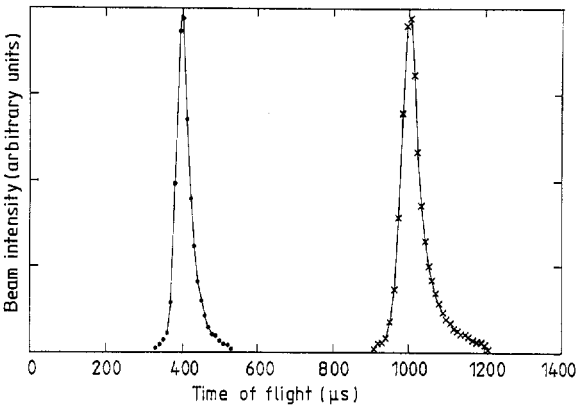

Figure 2 Detector signals with a pulsed helium beam expanding from a reservoir at 2.5 MPa. (●), First detector, 0.653 m from source; (×), second detector, 1.712 m from source.

The two gauges are situated at 0.653 m and 1.712 m from the pulsed beam source and the peak intensities of the two signals have been normalised to facilitate comparisons between them. The capacitor charging voltages, together with the delay between the pulses opening and closing the valve, were adjusted to minimise the time spread at the second beam detector.

The spread in arrival times at each detector is due to two components: the opening time of the valve (Δt_s) and the spread (Δt_v) due to the distribution of velocities in the beam. Following Gentry and Giese (1978) we assume these contributions combine like the convolution of two Gaussian distributions to give the total time spread (Δt) at the detector as:

$$\Delta t^2 = (\Delta t_s)^2 + (\Delta t_v)^2.$$

Measurements of Δt at both gauges allow estimates to be made of Δt_s and the velocity spread ($\Delta v/v$) in the beam. For the helium beam (figure 2) the (FWHM) values obtained are: $\Delta v/v = 4\%$ ($\pm 2.5\%$) for the velocity spread and $\Delta t_s = 25$ μs (± 4 μs) for the valve opening time. Adjusting the valve for shorter opening times resulted in longer time spreads at the furthest beam detector. The results indicate that, at the shortest valve opening times ($\Delta t_s = 12$ μs), the velocity spread ($\Delta v/v$) in the beam was approximately 10%.

Figure 3 shows the valve performance for a range of gases (H_2, He, Ne) with a single ion gauge detector located at a distance of 1.18 m from the beam source. Worst case beam velocity ratios ($\Delta v/v$) can be estimated by assuming none of the spread in arrival times is due to the valve opening time. The values obtained are 6.4% for H_2, 7.5% for He and 4.0% for Ne. The pronounced tail on each peak (figure 3) at longer flight times is due to scattering from the walls of the flight tube and was eliminated by improved beam collimation (cf figure 2).

Estimates of the beam intensity can be obtained from the measured peak ion currents and a knowledge of the sensitivity

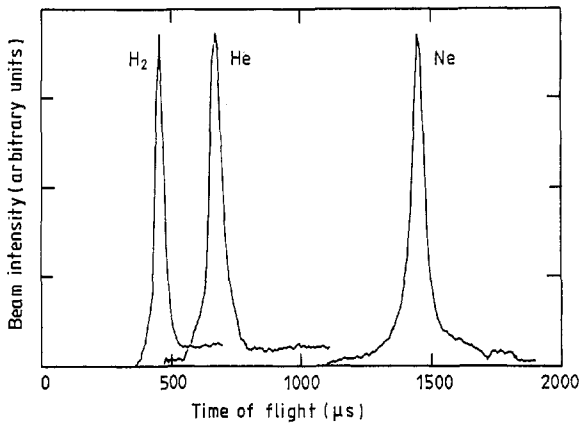

Figure 3 Valve performance for various gas species with a single detector located 1.18 m from the source. Peaks in increasing order of flight times are for beams of H_2, He and Ne.

of the commercial ion gauges used. At moderate opening times (20–30 μs) the intensity of a beam of helium atoms was 1.0×10^{22} atoms/sr/s.

More than 400 000 beam pulses have been produced with no appreciable wear in the valve components and no observable deterioration in the valve performance.

4 Summary

We have described the construction and performance of a novel pulsed molecular beam source. The source operates as a fast valve and uses the induced current repulsion in a light aluminium disc to provide the valve action. The opening time of the valve can be varied over the range 10–100 μs by adjusting the delay between the current pulses used to open and to close the valve. Results show that optimum performance is not necessarily obtained with the shortest valve opening times. This is particularly true in high resolution experiments where the detector is situated at large distances (over 1 m) from the source. In these instances longer opening times (20–30 μs) give beams with narrower velocity distributions and, consequently, beam pulses that have a narrower time spread at the detector.

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