Spatial profiles of effusive molecular beams and their dependence on gas species



1993 Meas. Sci. Technol. 4 1143

(http://iopscience.iop.org/0957-0233/4/10/019)

Meas. Sci. Technol. 4 (1993) 1143–1153. Printed in the UK

# Spatial profiles of effusive molecular beams and their dependence on gas species

**Stephen J Buckman, R J Gulley, M Moghbelalhossein and S J Bennett†**

Electron Physics Group, Atomic and Molecular Physics Laboratories, Research School of Physical Sciences & Engineering, Australian National University, Canberra, ACT, Australia

Received 30 March 1993, accepted for publication 4 May 1993

**Abstract.** The spatial profiles of molecular beams formed by both single and multicapillary sources have been investigated for He, Ne, Ar, Kr, $H_2$ and $N_2$. The profile measurements were undertaken at distances from the source exit and driving pressures which are typical of those used in atomic collision experiments (1–5 mm and 0.02–10 Torr respectively). The experimental results indicate the clear superiority of a capillary array source over a single tube source, of similar overall dimensions, in producing a well collimated molecular beam over a wide range of driving pressures and distances from the capillary exit. They also indicate that there is a measurable dependence of the beam profile on gas species, particularly at the higher pressures studied. The significance of this result for the relative flow, cross section normalization technique is discussed.

## 1. Introduction

Many research areas in atomic, molecular and surface physics require intense, collimated beams of atoms and molecules. The wide variety of techniques available for the production of such beams include simple single-capillary sources with an appropriate length to diameter ratio, and the combination of many such miniature tubes in a capillary array source. A large number of studies, both theoretical (see for example Giordmaine and Wang (1960), Olander and Kruger (1970), Lucas (1973), Murphy (1989) and references therein) and experimental (e.g. Giordmaine and Wang (1960), Hanes (1960), Jones *et al* (1969), Steinrück and Rendulic (1986), Adamson and McGilp (1986, 1988) and Adamson *et al* (1988), have been carried out on such sources in an attempt to characterize both the shape and absolute axial number densities of the beams they produce. In general these studies have shown a reasonable level of agreement between the experimental distributions for both single and multicapillary sources and those calculated from a variety of theoretical approaches, provided the distance from the source is large (see for example Adamson and McGilp 1986, Adamson *et al* 1988).

Most of the experimental measurements have either been conducted with relatively large (40 cm or greater), or unspecified, separations between the exit of the capillary source and the detector. However Jones *et al* (1969), Adamson and McGilp (1986, 1988) and Adamson *et al* (1988), measured angular distributions for single capillaries, at separations of 5 mm, 6–30 mm and 12 mm respectively. The data of Adamson and McGilp, for a separation of 12 mm, indicate the development of significant differences between distributions at relatively high pressures, i.e. at low Knudsen numbers (<1) (the Knudsen number based on the length $L$ of the capillary is $K_L = \lambda/L$ where $\lambda$ is the mean free path of the gas), presumably as a result of intermolecular collisions occurring within the capillary. The most extensive set of measurements to date are those of Adamson *et al* (1988), who measured angular distributions for a number of different single capillaries and made comparisons between the experimental distributions and those calculated using both Monte Carlo techniques and analytical expressions available in the literature. They found significant discrepancies between the experimental distributions and those calculated using the existing analytical expressions, but good agreement between experiment and the Monte Carlo approach. They also found no apparent differences in the distributions produced by glass or stainless steel capillaries of identical dimensions. As their work was motivated by a desire to understand the process of beam doping of samples in UHV technology, it was carried out at very low driving pressures corresponding to a situation where no intermolecular collisions occur (i.e. pure molecular flow).

† Present address: Aerophysics and Laser-Based Diagnostics Laboratory, Department of Physics and Theoretical Physics, Australian National University, Australia.

0957-0233/93/101143+11 $07.50 

There is, however, little or no information concerning the shape of such distributions close to the exit of the source, or how this shape varies as a function of both driving pressure and gas species at higher driving pressures, outside the molecular flow regime. This is somewhat surprising given the large number of atomic and molecular collision experiments which are performed by intersecting beams of particles with gas beams at or near the exit of the gas beam source, in order to maximise the available beam intensity. An important aspect of many of these experiments is the establishment of an absolute scale for the intensity of a scattered or ejected species. This usually requires an accurate knowledge of the respective beam profiles and the way in which they vary as a result of changing experimental parameters.

Thus, the principal motivation for the present experiments was to investigate the spatial profiles of molecular beams at distances from the beam source (1–5 mm) which are typical of those used in collision experiments. In particular, we were most interested in assessing the accuracy of some aspects of a technique which has become almost standard practice in the field of electron–atom (molecule) collisions—the relative flow technique (Srivastava *et al* 1976, Nickel *et al* 1989). This technique involves the comparison of scattered intensities for the gas of interest, whose scattering cross section is unknown, with that of a target whose cross section is known (usually helium), in order to place the cross section for the unknown species on an absolute scale. Its accurate application requires careful attention to experimental detail to ensure that either the measurements in both gases are carried out under identical conditions or, if this is not possible, the ramifications of any differences are well understood. The crucial requirement of the technique is that the interaction volume, usually defined as the overlap of the electron and molecular beams, should be identical for both gases. It is generally assumed that the shape of the molecular beams will be identical if the mean free paths for each gas in the region at the entrance to the capillary source are the same, and if the pressure conditions are such that intermolecular collisions do not have a significant effect on the shape of the distribution. In the latter case, a general empiricism which has been applied (Nickel *et al* 1989) is that the Knudsen number in the source region based on the diameter $d$ of the capillary, $K_d = \lambda/d$, should be much greater than one.

This requirement can place rather substantial restrictions on experiments that use a single capillary as a beam source. For instance, for a single capillary with a typical active diameter of 1 mm, the requirement that $K_d > 1$ implies an operating (driving) pressure for helium of less than 0.1 Torr. For many applications this would be too small to produce practical signal levels. Indeed, pragmatic considerations usually result in such experiments being conducted at much higher pressures in the intermediate, or Clausing, flow regime, where the mean free path is greater than the diameter of the capillary but less than the length. One other solution is to use a capillary array source which may have the same active area but which contains many smaller diameter capillary tubes. Such arrays are available with capillary diameters as small as 10 $\mu$m in which case the above condition is relaxed by a factor of 100, i.e. a driving pressure of 10 Torr may be used before the above Knudsen criterion is violated. Such sources also have the advantage that the ratio of axial intensity to total gas flow is much higher than for a single tube of comparable overall diameter. This is of great advantage in those applications where there are limitations on pumping speed. Hence, a further motivation for the present study was a direct comparison of the spatial profiles of molecular beams produced by both single and multicapillary sources, with particular emphasis on the implications of this comparison for typical atomic collision experiments.

The experimental apparatus and measurement techniques used in the present study are described in the next section. The results are then presented in section 3 and some conclusions and suggestions offered in section 4.

## 2. Experimental apparatus and procedures

The experimental measurements were carried out in a stainless steel, six-way-cross, high-vacuum chamber which was pumped by a 170 l $s^{-1}$ turbomolecular pump. The base pressure of the apparatus was typically $1 \times 10^{-9}$ Torr. One arm of the vacuum chamber was used as the entry port for the gas source—either the single capillary or capillary array—which was mounted centrally from a UHV flange. The single capillary tube was manufactured from Pyrex glass with an exit diameter of 1.0 mm and length of 15 mm resulting in a shape factor of $\gamma = d/L = 0.067$. Two capillary arrays were used. The first, which is typical of the type we use in this laboratory for electron scattering experiments, was constructed by mounting a segment of a commercially available array (Galileo Electro-Optics), which had a capillary diameter of 0.040 mm and length 1.0 mm ($\gamma = 0.04$), on a soft glass tube with an internal diameter of 1.0 mm. The active area of the array source contained

**Table 1.** A summary of the physical characteristics of the capillary sources used in this study.

| Source | Length (mm) | Tube diameter (mm) | Active diameter (mm) | Shape factor $\gamma = d/L$ |
|---|---|---|---|---|
| Glass tube | 15 | 1.0 | 1.0 | 0.067 |
| Glass array | 1.0 | 0.040 | 1.0 | 0.04 |
| Metal array | 3.0 | 0.050 | 0.89 | 0.017 |

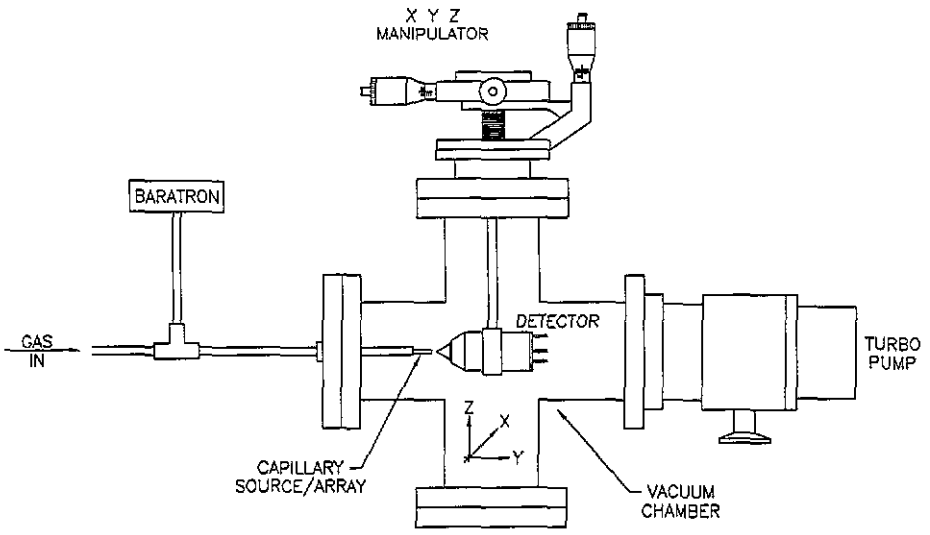


**Figure 1.** Schema of the vacuum chamber and gas handling system.

approximately 290 capillaries, representing an open area of approximately 50%. The other array (Srivastava 1992) was constructed from stainless steel and consisted of 96 capillaries of diameter 50 $\mu$m and length 3.0 mm ($\gamma = 0.017$) in an active diameter of 0.89 mm with a slightly smaller open area of about 30%. The physical details of the three sources are summarized in table 1.

The gas under study was routed to the capillary source via a regulator and needle valve (Granville Philips) and the pressure in the gas line immediately before the source was monitored with a capacitance manometer (MKS Baratron model 122A) with a stated accuracy of $\pm 0.5\%$. As the main aim of the present work was a comparative study of several sources and several gases, the accuracy of the absolute pressure was not of major importance. The vacuum chamber and gas handling system are shown schematically in figure 1.

The molecular beam was detected with a modified miniaturized version of a Bayard–Alpert ionization gauge. The detector (see figure 2) was housed in a long

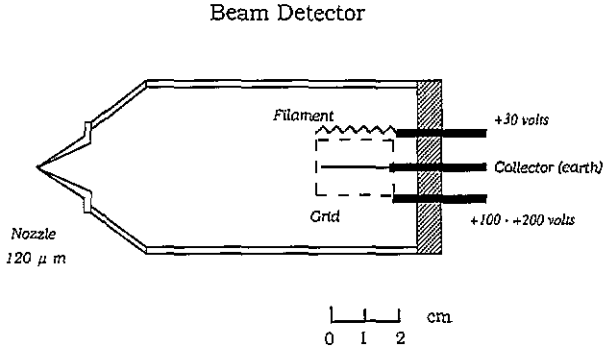


**Figure 2.** Schema of the miniature ion gauge detector used for the present study.

aluminium tube and the beam sampled through a 0.12 mm orifice located at the apex of a conical section mounted on the end of the aluminium tube. The purpose of the cone (interior and exterior angles 26° and 30°

**Table 2.** A summary of the range of pressures and corresponding mean free paths and Knudsen numbers used for each of the sources in the present study.

| Gas | $\delta$(Å) | $P$(Torr) | $\lambda$(mm) | $K_d$ | $K_L$ |
|---|---|---|---|---|---|
| **Glass capillary array** | | | | | |
| He | 2.65 | 0.062–9.23 | 1.58–0.011 | 39.5–0.263 | 1.58–0.011 |
| Ne | 2.36 | 0.116–9.83 | 1.057–0.012 | 26.4–0.3 | 1.06–0.012 |
| Ar | 2.94 | 0.02–10.0 | 3.95–0.008 | 98.75–0.20 | 3.95–0.008 |
| Kr | 3.44 | 0.037–5.473 | 1.56–0.011 | 39.0–0.263 | 1.56–0.011 |
| $N_2$ | 3.15 | 0.022–7.64 | 3.13–0.009 | 78.25–0.23 | 3.13–0.009 |
| $H_2$ | 2.34 | 0.079–3.346 | 1.58–0.037 | 39.5–0.925 | 1.58–0.037 |
| **Stainless steel capillary array** | | | | | |
| He | 2.65 | 0.125–9.44 | 0.783–0.011 | 15.7–0.22 | 0.261–0.004 |
| Ar | 2.94 | 0.057–7.48 | 1.39–0.011 | 27.8–0.22 | 0.463–0.004 |
| $N_2$ | 3.15 | 0.102–7.49 | 0.675–0.009 | 13.5–0.18 | 0.225–0.003 |
| **Single glass tube** | | | | | |
| He | 2.65 | 0.064–2.65 | 1.53–0.037 | 1.53–0.037 | 0.102–0.003 |
| Ar | 2.94 | 0.058–3.33 | 1.37–0.024 | 1.37–0.024 | 0.091–0.002 |
| $N_2$ | 3.15 | 0.021–3.11 | 3.28–0.022 | 3.28–0.022 | 0.219–0.001 |

respectively) was to minimize the amount of disturbance the detector entrance caused to the molecular beam under study. Provision was made to pump the enclosure via a number of slots in the periphery of the tube at its downstream end. However, an experimental investigation indicated this was neither necessary nor desirable, as an increase in sensitivity of as much as a factor of 50 was obtained when the detector was fully enclosed (with the exception of the entrance orifice) compared with its operation in a 'nude' configuration. This has also been noted by Adamson and McGilp (1986) and can be easily verified by some elementary considerations of conductance and pumping speed.

The source of electrons in the detector was a conventional tungsten filament which was biased at +30 V with respect to earth. The emitted electrons were accelerated to the grid by operating it at between +100 and +200 V with respect to earth. Positive ions, formed near the grid by electron impact ionization of the gas, were attracted to the central collector which was operated at earth potential. Both the electron current to the grid and the ion current to the collector were monitored and

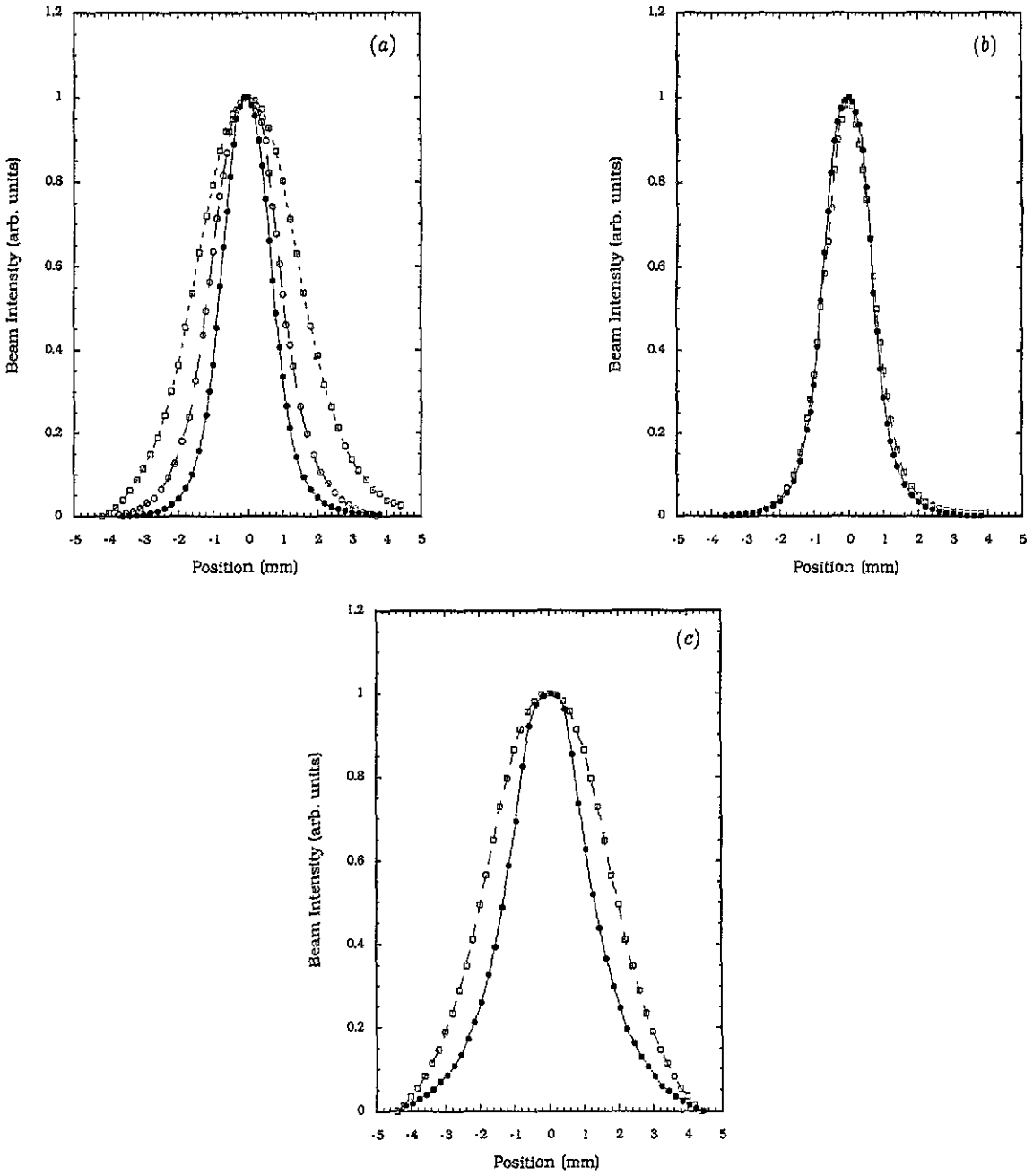


**Figure 3.** (*a*) The variation in the spatial profile of a helium beam, produced by a single tube 1.0 mm in diameter with a driving pressure of 0.98 Torr, at distances of 1.5 mm (●), 2.5 mm (○), and 4.5 mm (□) from the exit plane of the source. (*b*) The variation in the spatial profile of a nitrogen beam produced by a single tube, measured at a distance of 1.5 mm from the exit plane of the source, for driving pressures of 0.02 (●) and 3.11 (□) Torr. (*c*) As for 3(*b*) but at a distance of 4.5 mm from the exit plane of the source.

the operation of the detector was carefully characterized to ensure stability over a wide range of gas pressures, and to ensure linearity between grid and collector current.

The detector was attached to an *xyz* manipulator (Huntington PM-600) mounted from another arm of the six-way-cross and could be moved $\pm 12$ mm in the *xz* plane perpendicular to the beam direction, and $+20$ mm along the beam *y* axis. The relative position of the detector, as monitored via micrometer screw gauges, could be determined to within 1 $\mu$m and was reproducible to within 10 $\mu$m. The distance between the exit plane of the gas jet and the detector orifice was obtained from the geometry of the system and could be checked external to the system by a travelling microscope. The uncertainty in this distance is estimated to be less than 0.1 mm.

Beam profiles were measured by scanning the detector in the *z* direction (typically over a range of $\pm 5$ mm) in 0.1 or 0.2 mm increments from the beam centre, which was readily determined from the symmetry of the distribution. Although the detector was positioned manually, the data acquisition at each increment, which involved measuring the driving pressure and grid and collector currents, was performed under computer control. The delay between measurements at consecutive positions was varied between 0 and 30 s with no observable effect on the measured distributions. The final distributions were derived by normalizing the collector current measurements at each point to both grid current and pressure. Both these quantities varied by less than 1% during a scan.

Measurements for both single and multicapillary sources of 1.0 mm active diameter were taken for a range of source–detector distances between 1.5 and 10.0 mm and for a variety of gases. This enabled comparisons to be made of:

(i) the profiles of beams produced by both single tube and array sources as a function of gas species;
(ii) the profiles of beams produced by both single tube and array sources as a function of gas pressure;
(iii) the relative merits of single tube versus array sources for molecular beam formation.

The following gases were used in the course of these experiments—He, Ar, Ne, Kr, $N_2$, $H_2$, and $SF_6$. Problems were encountered in obtaining stable, reproducible results with both $H_2$ and $SF_6$ due, we believe, to the adsorption/desorption of these gases onto the relatively hot surfaces of the ion gauge detector. In the case of $H_2$, the problem was overcome by waiting for stability to occur. However in the case of $SF_6$, stability could not be achieved, and these results have not been considered in the analysis.

A direct comparison of the profiles produced by different gases was one of the major aims of this study. Rather than make this comparison as a function of driving pressure, it is more meaningful to do so as a function of the mean free path given by

$$\lambda = \frac{1}{\sqrt{2}N\pi\delta^2} \tag{1}$$

where $N$ is the number density of the gas in the source region and $\delta$ is the molecular hard sphere diameter. The values for the hard sphere diameters are derived from a number of sources, including experimental viscosity and heat conductivity studies, and from van der Waal's equation. In some cases there is considerable uncertainty ($\approx 20\%$) in the hard sphere diameters available in the literature for the gases used in this study. Whilst the effects of the uncertainties in these values are translated directly into the comparisons we make in the next section, we do not believe that they affect the overall conclusions. The pressure and mean free path values, and the corresponding Knudsen numbers, used in the present study are summarized in table 2.

## 3. Results and discussion

There are several ways in which the relative merits of beam forming devices might be compared, depending on the particular requirements of the experiments in which the beams are to be used. For example, a common 'figure of merit' which has been used in the past is the ratio of the peak (axial) intensity of the distribution to the total gas throughput. As our study has been particularly concerned with the spatial extent of such beams,

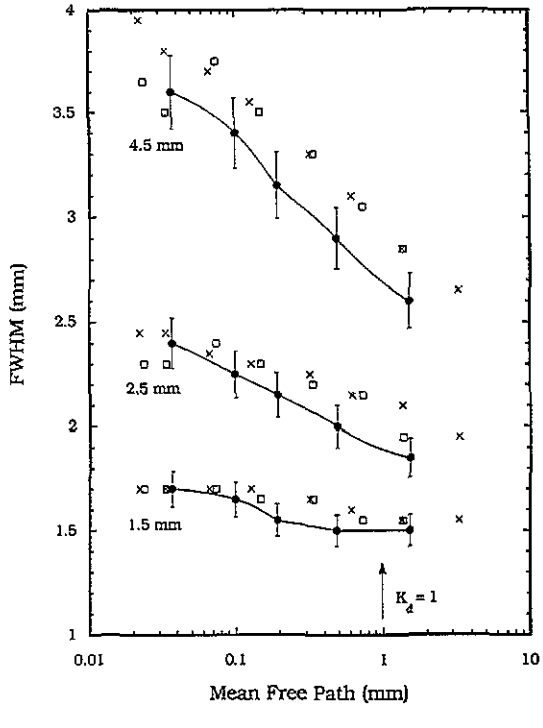


**Figure 4.** The variation of the FWHM with MFP for beams of He (●), Ar (□) and $N_2$ (×), produced by a single 1.0 mm diameter capillary tube at distances of 1.5, 2.5 and 4.5 mm from the exit plane of the source. The vertical arrow indicates where $\lambda = d$.

and the ramifications that any differences between gas species may have for atomic collision cross section measurements, most of our comparisons will be made in terms of the full-width-at-half-maximum (FWHM) of the distributions. These have been determined directly from the experimental measurements and no attempt has been made to fit the data with a specific functional form, although some comparisons with theoretical predictions have been made and will be discussed later. The finite size of the sampling orifice was also taken into account by numerically unfolding its contribution to each of the measured spatial profiles. As expected, this effect was largest at the smallest source–detector separation of 1.5 mm, where it resulted in a reduction of about 5% in the FWHM from the measured value.

### 3.1. Single capillary

Measurements for the single 1.0 mm diameter glass capillary were carried out for He, Ar and $N_2$, at driving pressures between 0.021 and 5.0 Torr. The upper limit to this pressure range is about half that for the capillary

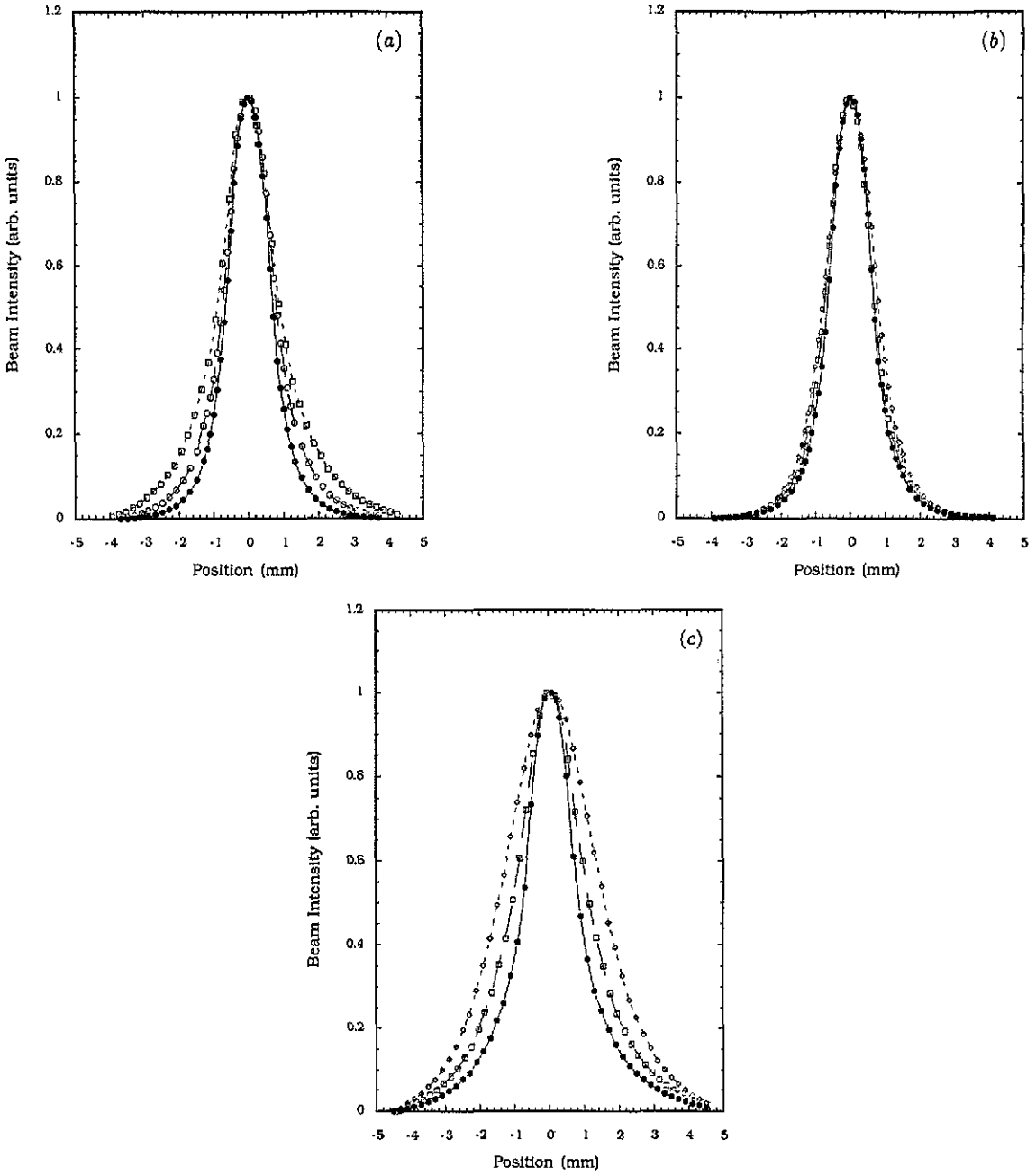


**Figure 5.** (*a*) The variation in spatial profile for a helium beam produced by a glass capillary array (see text) at distances of 1.5 mm (●), 2.5 mm (○), and 4.5 mm (□) from the exit plane of the array, for a driving pressure of 1.0 Torr. (*b*) The variation in the spatial profile of a neon beam produced by a glass capillary array, measured at a distance of 1.5 mm from the exit plane of the array, for driving pressures of 0.116 (●), 2.13 (□), and 9.83 (◇) Torr. (*c*) As for 5(*b*) but at a distance of 4.5 mm from the exit plane of the array.

array measurements, mainly as a result of the higher gas throughput for this source and the pumping speed of the turbomolecular pump used. Representative examples of the beam profiles obtained for these gases, at several values of the source–detector separation, are shown in figure 3(*a*) for helium at a driving pressure of 0.98 Torr. The large angular divergence of the beam is immediately obvious from this figure, with the FWHM increasing by over 100% as the source–detector separation is increased from 1.5 to 4.5 mm. In figures 3(*b*) and 3(*c*) we show the effect on the spatial profile of a $N_2$ beam, at source–detector distances of 1.5 and 4.5 mm respectively, of increasing the driving pressure from 0.021 to 3.11 Torr. At the closer distance there is essentially no difference over this broad pressure range in the FWHM of the profiles. However, at 4.5 mm there is a noticeable increase (about 50%) in the width of the beam. This pressure range corresponds to a variation in mean free path between 3.2 mm and 0.022 mm, that is from a region where $d<\lambda<L$ to one where $\lambda \ll d$. Thus, the increase in width is undoubtedly due to the influence of increased intermolecular collisions within the source tube, and the magnification of these effects by the larger distance to the detector.

Figure 4 enables a more comprehensive assessment of the effects of pressure on the spatial distribution from such a source to be made. In this figure, the variation of the FWHM at three detector distances (1.5, 2.5 and 4.5 mm) is shown as a function of mean free path (refer to table 2 for the associated pressures) for He, Ar and $N_2$. As may be expected from geometrical considerations, this variation is largest at the greatest source–detector separation. It is also apparent, particularly at distances of 2.5 and 4.5 mm, that there are some differences between the gases. In all cases the measured widths for helium at a given mean free path are less than or equal to those for either argon or nitrogen. This is discussed further in section 4.

### 3.2. Capillary arrays

An extensive series of measurements using six different gases and a wide range of driving pressures has been carried out for the glass capillary array. Figure 5(*a*) shows beam profiles measured at a number of different detector distances for helium at a driving pressure of 1.0 Torr. Whilst there is a noticeable increase in the width of the wings of the profiles as the distance is increased, the FWHM only increases by about 10%, indicating the superior collimation which can be achieved with the array at such pressures. Figures 5(*b*) and 5(*c*) show the variation in the profiles as a function of driving pressure at distances of 1.5 and 4.5 mm respectively, for neon at pressures of 0.116, 2.13 and 9.83 Torr. At 1.5 mm there is less than a 10% increase in the FWHM of the beam for a corresponding increase of almost a factor of a hundred in driving pressure, indicating a high degree of collimation from the capillary array. At a distance of 4.5 mm the increase in the beam width is considerably more marked, and is due to both geometrical factors and the effects of collisions.

The entire data set for this array is summarized in figure 6, where the FWHM at various detector distances

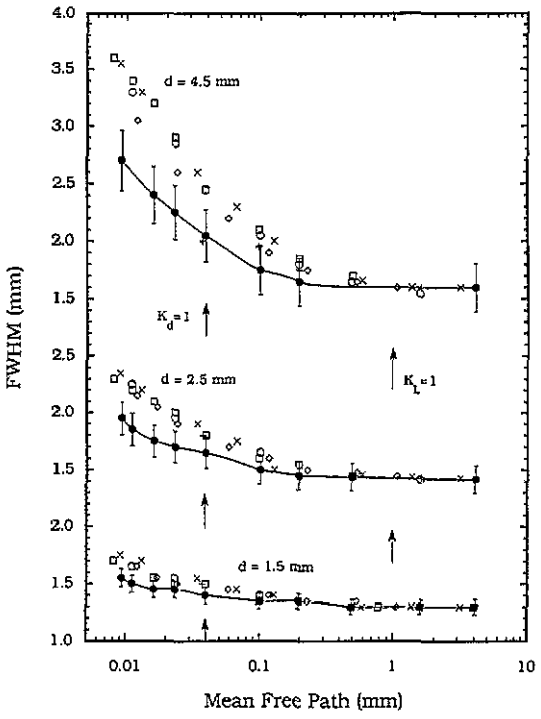


**Figure 6.** The variation of the FWHM with MFP for He (●), Ar (□), Kr (○), Ne (◇), $N_2$ (×) and $H_2$ (+) beams produced by a glass capillary array at distances of 1.5, 2.5 and 4.5 mm from the exit plane of the array. The vertical arrows indicate where $\lambda = d$ and $\lambda = L$.

for each of the gases studied are plotted as a function of the mean free path. The general trend is the same for each distance, the FWHM increasing as the mean free path decreases (i.e. as the pressure increases). This increase is once again most marked at the largest distance (4.5 mm). It is also clear from this figure that the FWHM for helium is substantially smaller than for the other heavier gases at high driving pressures. Indeed there are apparently two families of curves, one for helium and one for the other gases, at each detector distance, with the departure between the two occurring at a mean free path of approximately 0.2 mm. One possible exception to this behaviour occurs for $H_2$, where the small amount of data, particularly at 4.5 mm, shows a FWHM which is similar to that of helium. At the highest pressures studied, corresponding to mean free paths of slightly less than 10 $\mu$m, the differences between the FWHM for helium and nitrogen beams at detector distances of 1.5, 2.5 and 4.5 mm are 13%, 20% and 30% respectively. Again this will be discussed further in the next section.

A less extensive set of measurements was carried out for the smaller metallic capillary with only three gases—He, Ar and $N_2$—being studied. In figure 7(*a*) the variation of the width of a helium beam is shown as a function of detector distance for a pressure of 0.99 Torr. Whilst the absolute value is smaller, as expected, than for the glass array (see figure 5), the divergence of the beam is comparable. In figures 7(*b*) and (*c*) the variation in the beam profile as a function of driving pressure is shown for detector distances of 1.5 and 4.5 mm respect-

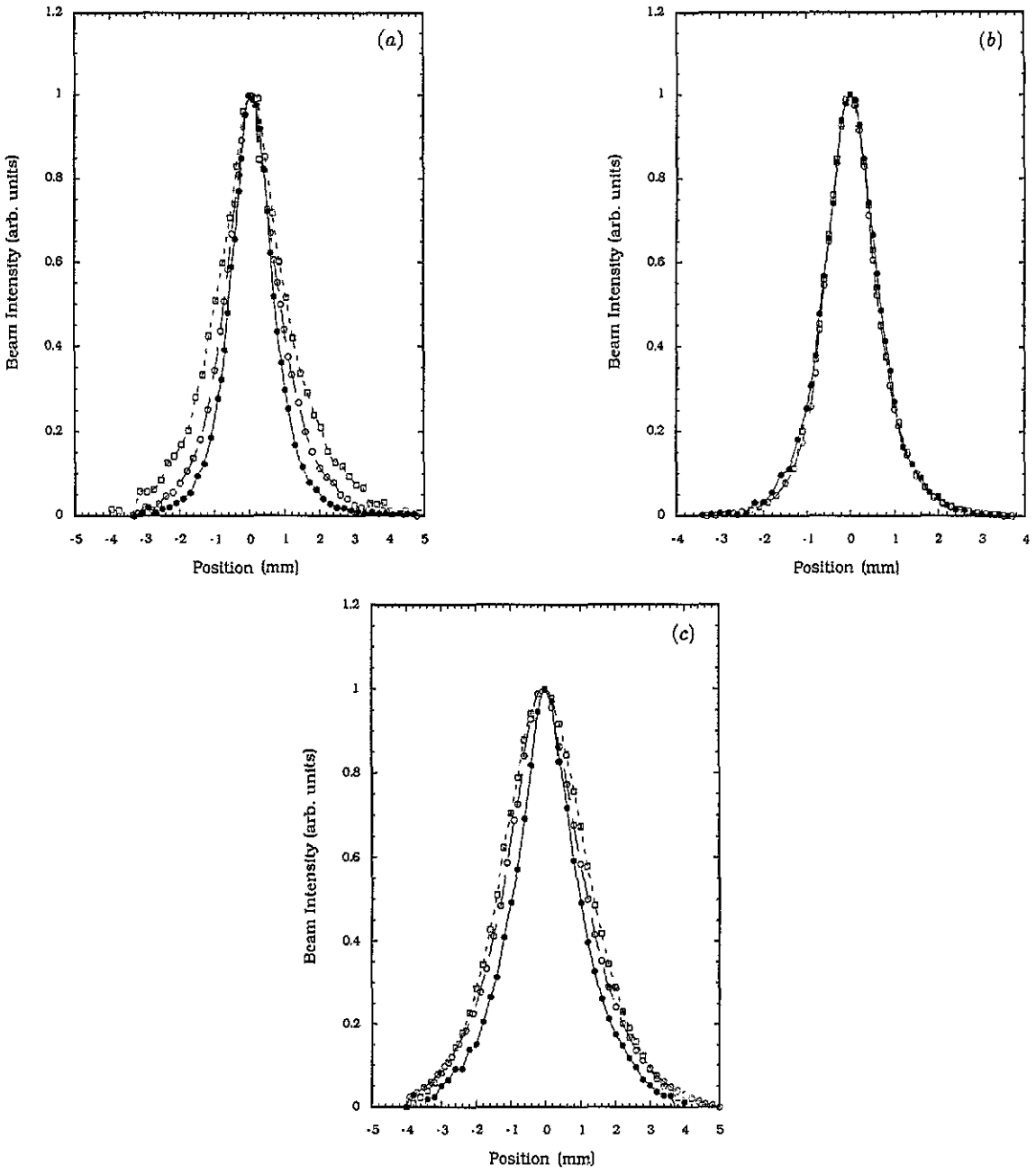


**Figure 7.** (*a*) The variation in spatial profile for a helium beam produced by a metal capillary array (see text) at distances of 1.5 mm (●), 2.5 mm (○), and 4.5 mm (□) from the exit plane of the array, and at a driving pressure of 0.99 Torr. (*b*) The variation in the spatial profile of an argon beam produced by a metal capillary array, measured at a distance of 1.5 mm from the exit plane of the array, for driving pressures of 0.057 (●), 2.33 (○) and 7.48 (□) Torr. (*c*) As for 7(*b*) but at a distance of 4.5 mm from the exit plane of the array.

ively. It appears that there is essentially no measurable effect on the profile at 1.5 mm as a result of increasing the driving pressure by a factor of 130. At 4.5 mm the increase in width is of the order of 40% over this pressure range. Once again we summarize the entire set of data for the metal array by plotting the variation in FWHM as a function of mean free path for the various detector distances in figure 8. Similar, though slightly less dramatic, differences as a function of gas type are shown here, as in figure 6, for the glass capillary. The results for helium are once again significantly smaller than those for the other gases and this difference may extend to slightly larger values of the mean free path than was the case for the glass capillary. For comparison we note that at the lowest mean free path studied, about 10 $\mu$m, the differences between the FWHM for helium and nitrogen at 1.5, 2.5 and 4.5 mm are 4%, 5% and 14%.

### 3.3. Comparisons

Whilst some comparative information on the performance of the respective sources can be obtained from

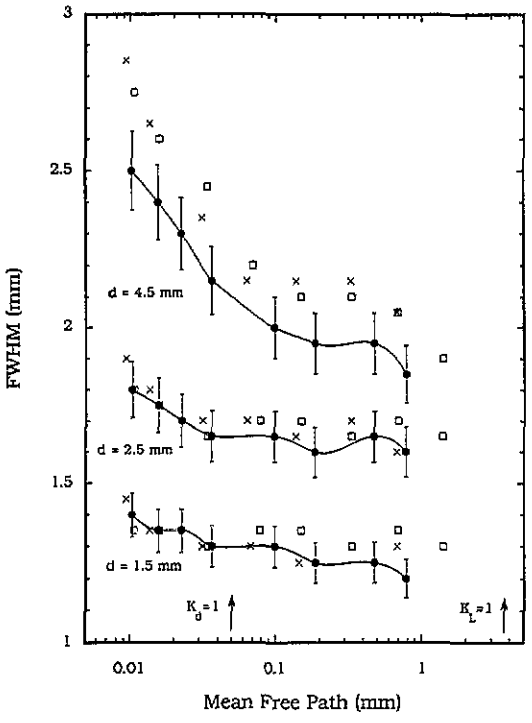


**Figure 8.** The variation of the FWHM with MFP for He (●), Ar (□) and $N_2$ (×) beams produced by a stainless steel capillary array at distances of 1.5, 2.5 and 4.5 mm from the exit plane of the array. The vertical arrows indicate where $\lambda = d$ and $\lambda = L$.

figures 3–8, it is perhaps instructive to make some direct comparisons between the profiles produced from the single glass tube and the glass array, both of which have identical active diameters of 1.0 mm. This is done in figures 9(*a*) and (*b*), at source–detector separations of 1.5 and 4.5 mm respectively, and a helium driving pressure of 0.99 Torr. The advantage of the higher degree of collimation available with the array is most evident at larger distances; for example at a distance of 4.5 mm from the source exit the beam profile from the single tube has a FWHM which is 100% larger than that for the array. At a distance of 1.5 mm, it is only about 20% larger.

In figures 10(*a*) and (*b*) we compare the FWHM of a helium beam produced by both capillary arrays and the single tube at source–detector distances of 1.5 and 4.5 mm. The advantage of using an array to obtain higher spatial localization is once again immediately obvious. At a distance of 1.5 mm (figure 10(*a*)) the FWHM of the beam produced by the metal array is, as expected, slightly smaller than that from the glass array. The corresponding result at 4.5 mm indicates the beam from the glass array is smaller than that from the metal array. Given both the smaller value of the shape factor $\gamma$ and the smaller active area of this array this is a surprising and somewhat anomolous result.

We have also made some comparisons of the present experimental results with distributions calculated using the analytical expressions of Olander and Kruger (1970). These expressions and the various descriptions which are used for the entrance and exit number densities have been discussed in detail by Adamson and McGilp (1986) and will not be repeated here. We found that the calculated distributions were significantly different from those measured at all detector distances and pressures studied here. In general they were too narrow and too peaked when compared with the experimental results. A similar result has been observed by Adamson *et al* (1988) for very low driving pressures and at a source–detector distance of 12 mm from various single capillaries. They

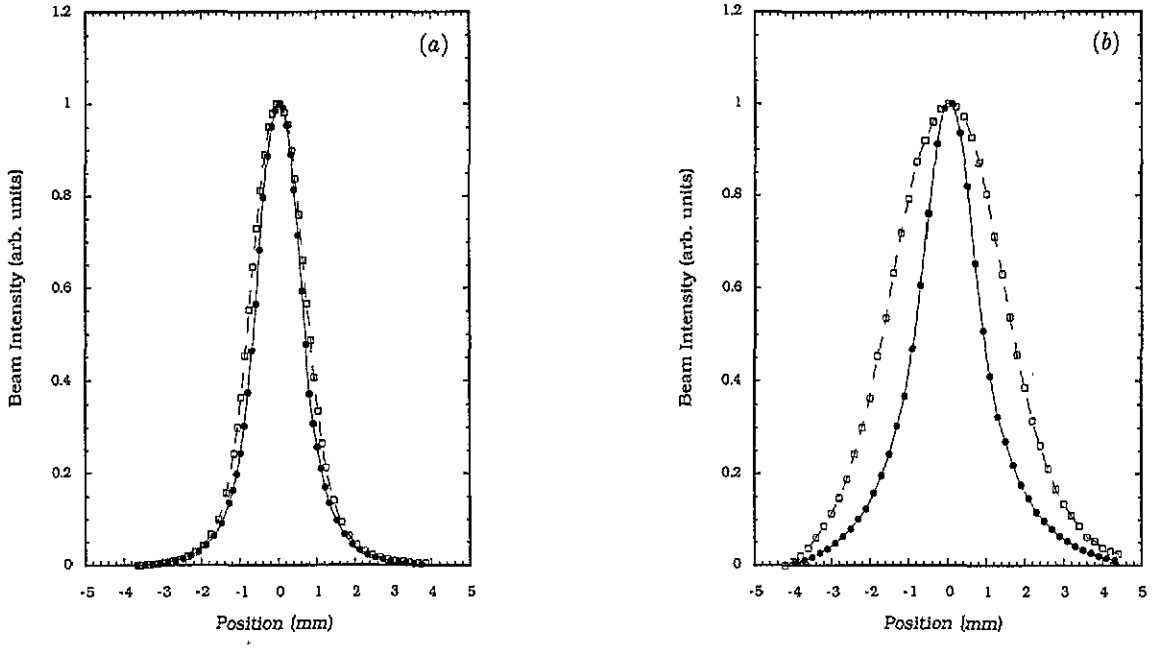


**Figure 9.** (*a*) A comparison of the beam profiles obtained with the single tube (□) and the glass capillary array (●) at a source–detector distance of 1.5 mm for a helium beam at a driving pressure of 0.98 Torr. (*b*) As (*a*) but at a distance of 4.5 mm.

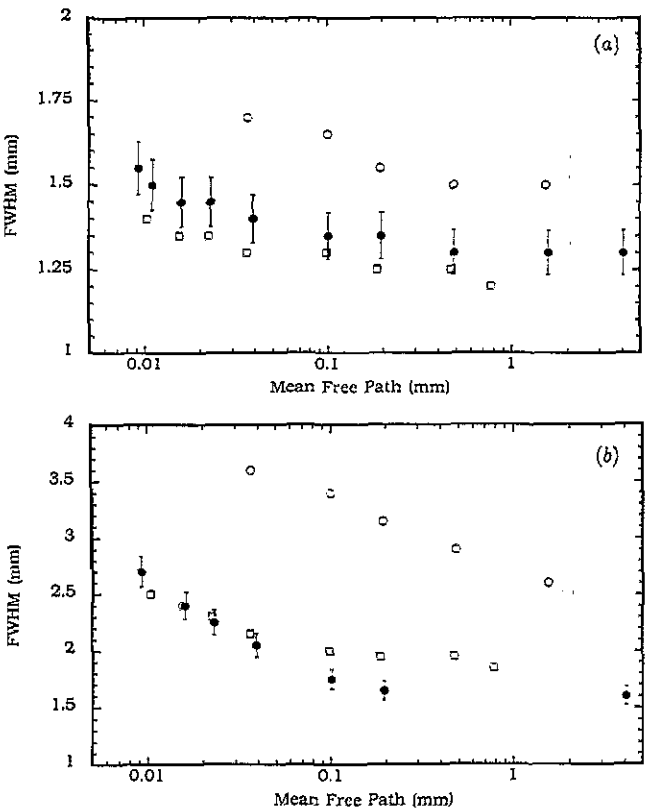


**Figure 10.** (*a*) The variation of the FWHM with MFP for a helium beam produced by a single tube (○), the glass capillary array (●), and the stainless steel array (□) at a distance of 1.5 mm from their exit planes. (*b*) As (*a*) but at a distance of 4.5 mm.

concluded that this was due to the breakdown of the assumption, implicit in the analytical expressions, that the capillaries behave as point sources. Thus, it is not surprising that these expressions also fail in the present case where the point source assumption is even less credible at the smaller source–detector distances.

## 4. Conclusions

A number of conclusions, of significance for measurements of charged particle scattering cross sections using crossed beam geometries, can be drawn from the work described in this paper. Firstly it is evident that in cases where a spatially well defined atomic or molecular beam is required, the use of a capillary array source rather than a single capillary is favoured. This is particularly true when the interaction volume for such experiments cannot be located very close to the exit of the source, but must be situated some distance from it. Our measurements show that when the interaction volume is situated more than about 2 mm from a 1 mm active diameter source, there are clear advantages in using a capillary array. It follows from this that the use of a capillary array is also an advantage when there are restrictions on pumping speed as they provide a superior ratio of centreline intensity to total flow than a single capillary tube of similar diameter.

Secondly, it appears that, despite the obvious differences in the absolute size of the beams, there are only slight differences in the dependence of the width of the beam profile on pressure (or mean free path) for beams produced by capillary arrays or single capillaries. Therefore, if the absolute size of a molecular beam at a given pressure is not of concern, then a single tube may be adequate for its production.

Thirdly, and of most relevance in the context of the present study, there is a significant difference in the widths of the beam profiles for different gases as the driving pressure is increased. In the case of the glass capillary array studied in detail here, this difference becomes significant when the mean free path of the gas is about twice the diameter of the capillaries. For this ratio of mean free path to diameter, the differences are small ($\approx 5\%$) but they increase rapidly with increasing pressure. This effect appears to be independent of the type of source used to produce the beam, and also appears to be loosely associated with the mass of the species, with helium always producing beams of narrower width. We can only speculate as to the reasons for these differences. At the pressures at which they manifest themselves, there is clearly an increased number of collisions occurring both between the atoms or molecules in the beam and between the beam constituents and the walls of the source tube(s). As the observed effects are similar for both glass and stainless steel capillary arrays, we assume that collisions with the walls of the tubes are of secondary importance (see also Adamson *et al* 1988) in producing the dependence of the beam widths on gas species, and that the differences are principally due to the different collision cross sections for mutual scattering by these gases.

These differences, regardless of their source, may be of great importance in those studies mentioned earlier in which absolute cross section determinations are based on measurements of the ratios of scattered particle intensities for different gases. In our own field of experimental research, electron–atom/molecule scattering, the standard gas which is almost universally used to obtain absolute scattering cross sections, via the relative flow technique, is helium. The present results indicate substantial differences between the size of helium beams and almost all other gas beams, at equivalent mean free paths, when the mean free path is small. Accordingly, we caution that great care should be exercised when using such techniques and, that as a general rule of thumb, gas pressures should always be such that the associated mean free path is larger than twice the smallest dimension of the capillary.

## Acknowledgments

It is a pleasure to acknowledge the skills of John Gascoigne who constructed the gas sources used in the present study, as well as those of Kevin Roberts and Graeme Cornish who constructed the detector and vacuum system. We are grateful to Malcolm Elford for many stimulating discussions and suggestions during the

course of this work. RJG thanks the Australian National University for the provision of a Postgraduate Research Award and MM the Iranian Government for the provision of a Research Scholarship. We thank both Santosh Srivastava and Sandor Trajmar for providing a sample of the metal capillary arrays used at the Jet Propulsion Laboratory, CalTech.

## References

Adamson S and McGilp J F 1986 *Vacuum* **36** 227
—— 1988 *Vacuum* **38** 463
Adamson S, O'Carroll C and McGilp J F 1988 *Vacuum* **38** 341
Giordmaine J A and Wang T C 1960 *J. Appl. Phys.* **31** 463
Hanes G R 1960 *J. Appl. Phys.* **31** 2171
Jones R H, Olander D R and Kruger V R 1969 *J. Appl. Phys.* **40** 4641
Lucas C B 1973 *Vacuum* **23** 395
Murphy D M 1989 *J. Vac. Sci. Technol.* A7 3075
Nickel J C, Zetner P W, Shen G and Trajmar S 1989 *J. Phys. E: Sci. Instrum.* **22** 730
Olander D R and Kruger V 1970 *J. Appl. Phys.* **41** 2769
Srivastava S K 1992 *Private Communication*
Srivastava S K, Chutjian A and Trajmar S 1976 *J. Chem. Phys.* **63** 2659
Steinrück H P and Rendulic K D 1986 *Vacuum* **36** 213