A Thermal Energy Molecular Beam Source for Use in Scattering Experiments

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A new nozzle source is discussed that produces a high-intensity molecular beam with very small dispersion in velocity. When signal-to-noise ratio in scattered beam experiments is used as a measure of performance this source is shown to be approximately equal in quality to a Kantrowitz-Grey source of comparable size. Furthermore it is argued that many existing Kantrowitz-Grey sources could be operated as simple nozzle sources with no appreciable loss in performance. The present source has several new features. The beam intensity is uniform over the beam cross section. Source performance is not strongly dependent on skimmer geometry; hence, a simple collimating hole in a plate suffices. Source performance is quite insensitive to the size of the collimating hole and its distance from the nozzle; thus, they may be adjusted to tailor the size and shape of the beam to the particular application. The present source may be uniquely suitable for a proposed new method of beam collimation.

1. Introduction

EXPERIMENTAL determinations of velocity and spatial distributions of thermal molecular beams, scattered either by a gas or at a surface, are limited by the ratio of the scattered beam signal to the noise due to background gas in the vacuum test chamber.[1,2] The signal-to-noise ratio would be increased by increasing the intensity of the incident molecular beam. Interpretation of scattering measurements in terms of the scattering mechanism may be achieved only if the velocity distribution in the incident beam is known, and this interpretation would be least difficult if the incident beam were monoenergetic.

Kantrowitz and Grey[3] proposed a beam generating device which would in principle produce a nearly monoenergetic molecular beam with flux intensity orders of magnitude higher than that of an effusive source of comparable size.

Becker and Henkes[4] have developed a working beam source based on this scheme. Bier and Hagena[5,6] studied conditions for achieving maximum flux intensity, and considered condensation in the jet and jet-skimmer interactions. Recently Hagena et al.[7] have developed a source with a maximum axial argon particle flux intensity of 7×10^{18} particles/sterad-sec. The axial flux from an effusive source, having a hole diameter equal to the skimmer diameter of Ref. 7 (1.00 mm), and operating at a Knudsen number of unity based on hole diameter, is 4.5×10^{16} particles/sterad-sec.

A new nozzle source is reported in this paper which also produces a high-intensity molecular beam with a very narrow spread in speed distribution, and has several advantages over previous nozzle sources of the Kantrowitz-Grey type. The source is of very simple design, and can be aligned easily and accurately by eye; the shape and size of the skimmer and distance from nozzle to skimmer do not strongly affect source performance thus these can be varied to tailor the shape and size of the molecular beam; although the particle flux per steradian on the beam axis is lower than that of a Kantrowitz-Grey source of camparable size, the flux intensity is essentially uniform over the beam cross section. Consequently, if signal-to-noise ratio (see below) is used as a measure of performance this source compares favorably with the more complex Kantrowitz-Grey source. For clarity the present source will be referred to as simply a nozzle source and all other nozzle sources will be called Kantrowitz-Grey sources.

The nozzle source is shown schematically in Fig. 1. The small nozzle (1) generates a continuum freejet, that enters the source chamber (3) where the bulk of the gas rejected by the collimator (2) is removed by the pump. The source collimator, which defines the angular spread of the beam entering the test chamber, is simply a hole in a flat plate; it replaces the conically shaped skimmer in the Kantrowitz-Grey source. Transition in the jet occurs very close to the nozzle, on the scale of distance from nozzle to collimator, in contrast to the Kantrowitz-Grey arrangement where the skimmer is located in the transition region. There are three length scales which differ in order of magnitude: the throat diameter d_e (here roughly 0.02 mm); the axial distance in the freejet from the nozzle exit to the onset of translational freezing x_t; the distance from the nozzle exit to the source collimator a (here $0.5 \sim 1.0$ cm) where $a \gg x_t \gg d_e$. Therefore, although the jet expands to high Mach number before transition (insuring a beam with a narrow spread in velocities), the flow of jet gas and background gas may be treated as simple molecular flow on the scale of nozzle-collimator distance a. For some applications it may be desirable to include a second collimator and collimating chamber between the source and test chambers. It will be shown below that in principle the presence of two collimators does not affect the uniform distribution of flux intensity across the molecular beam.

The manner in which flux intensity across the molecular beam (referred to as flux distribution) depends on source parameters is considered in Sec. 2. It appears from these considerations that a Kantrowitz-Grey source could be operated as a simple nozzle source and under such conditions the skimmer geometry becomes relatively unimportant.

Experimental results obtained with the present nozzle source are presented in Sec. 3. Flux distribution measure-

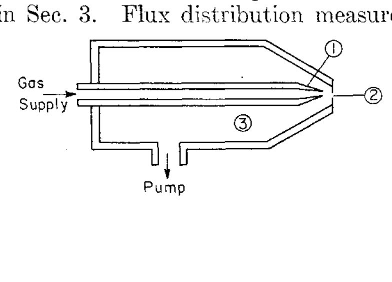

Fig. 1 Nozzle source schematic.

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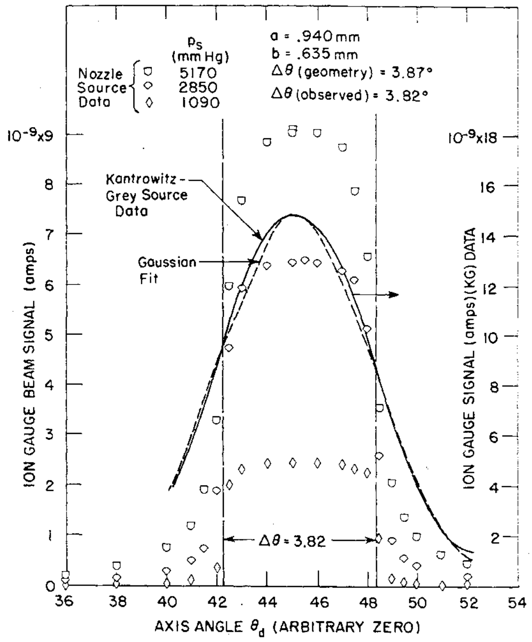

Fig. 2 Detector signal vs axis angle.

ments were made across the beam and flux intensity and time-of-flight measurements were made on the beam axis. The measurements were performed for various values of nozzle supply pressure p_s, and nozzle collimator spacing a. Two collimators were used, one approximately 0.635 mm square (0.64 by 0.62 mm), and one 1.00 mm square. The performance of the nozzle source is compared in Sec. 4 with the performance of a Kantrowitz-Grey source built in this laboratory based on a design by Campargue.[8] Both sources were studied in the same vacuum system and with the same detectors. A new method of beam collimation is proposed in the Appendix.

2. Beam Flux Distribution

Distributions of flux intensities over the beam cross sections (flux distributions) are analyzed for the nozzle source and Kantrowitz-Grey sources in this section, and the results are used to assess relative quality of source operating conditions.

Consider first a source consisting of a nozzle, source chamber and skimmer. The flux distribution depends on the magnitudes of x_t and a, and on the diameter (or width) of the skimmer opening b, and on the Mach number in the jet at transition M_t. Three limiting cases defined by limiting relations among these four parameters are examined. In all cases it is assumed that the skimmer subtends a small planar half-angle with respect to the nozzle, exit, i.e., $\theta_s \simeq b/2a, \ll 1$, and that $M_t \gg 1$. The analysis is simplified by assuming that translational freezing occurs abruptly and completely on a spherical front at some distance x_t from the nozzle exit.

Case 1: $b/2a = 0[M_t^{-1}]$, $x_t \simeq a$ (0 [ ] implies of the same order of magnitude)

Since M_t is a measure of the ratio of directed speed to thermal speed the beam divergence at the skimmer plane is of order M_t^{-1}. (Divergence here means angular divergence of beam particles crossing a single point in the skimmer plane and should not be confused with the beam half-angle dimension). The half-angle dimension of the molecular beam is of the order of the beam divergence, i.e., of order $b/2a$ or θ_s. The beam flux distribution at a distance from the skimmer which is large compared to a is not uniform over the beam cross section but decreases by order unity over the dimension of the beam.

Case 2: $b/2a \gg M_t^{-1}$, $x_t \simeq a$

Since beam divergence is small compared to θ_s the half-angle dimension of the molecular beam is equal to θ_s. The flux per steradian to a detector located downstream of the skimmer, within the half angle θ_s, will be essentially constant and equal to the flux per steradian that crosses the skimmer, and will drop to zero over a planar angle at the periphery of the beam which is of the order of M_t^{-1}, i.e., very small compared to the beam half angle.

From this description of idealized models (jet-skimmer interactions are neglected) it appears that a Kantrowitz-Grey source operated under the conditions of case 2 would produce a beam with uniform flux distribution. In practice, however, jet-skimmer interactions might cause the flux distribution to be as nonuniform as in case 1; furthermore, to achieve such extremely large values of M_t may cause appreciable condensation in the expanding jet. A uniform flux distribution may be achieved without these difficulties by operating under conditions of case 3, where translational freezing occurs far from the skimmer.

Case 3: $b/2a \geq 0[M_t^{-1}]$, $x_t \ll a$

The jet particle flux that crosses an arbitrary point in the skimmer orifice plane comes from an area of the transition "surface" with radius $y_t = 0[x_t/M_t]$, since the divergence of particles at the transition surface is of the order M_t^{-1}. The angular divergence of particles, $\delta\theta$, crossing a point at the skimmer plane is then $0[M_t^{-1}\cdot x_t/a]$. Since M_t^{-1} is at most of order $b/2a$ or θ_s, it is evident that $\delta\theta \lesssim 0[\theta_s\cdot x_t/a]$. Thus with $x_t/a \ll 1$ the beam divergence at the skimmer, $\delta\theta$, is small compared to θ_s. By the arguments in case 2, one concludes that the beam flux distribution will be uniform within the beam half-angle θ_s, and will drop to zero over a planar angle at the periphery of the beam which is of order $\delta\theta$, i.e., small compared to the beam half-angle. This analysis treats a limiting case of the "quitting surface" model of Anderson and Fenn,[9] and these conclusions agree with their relation for flux intensity when carried to the limits of the present case.

These geometric arguments may be interpreted in terms of a temperature or Mach number associated with particle velocities in the direction perpendicular to the jet axis. Accordingly the analysis predicts an a^{-2} dependence for perpendicular temperature $T_\perp$ at large a, instead of the a^{-1} dependence predicted in theory by Edwards and Cheng[10] and Hamel and Willis.[11] However, the velocity distribution analysis of Edwards and Cheng[12] predicts that most of the particles near the jet axis have a perpendicular thermal spread which varies as a^{-2} for large a, while a very small fraction of particles with a much larger perpendicular thermal spread dominate $T_\perp$, and these impose the a^{-1} dependence. Consequently, for the present flux distribution analysis, an a^{-2} dependence for $T_\perp$ based on geometric arguments is appropriate.

The nozzle source reported in this paper operates under the conditions defining case 3. The sources reported in Refs. 8 and 12 operate under conditions defining case 1. Several other investigators have developed sources which evolved from the original Kantrowitz-Grey scheme but in fact yield maximum axial flux intensities under the conditions defining case 3.[7,9,13,14] Case 3 is idealized by the condition, which is met in the present nozzle source, that the background gas in the source chamber does not significantly scatter the jet gas. This condition is not met at maximum axial flux intensity and the resultant jet scattering produced nonuniform flux distributions across the beams reported in Refs. 7 and 9 (flux distributions were not reported in Refs. 13 and 14).

It is thus evident that maximum (on axis) flux intensity must be sacrificed by reducing nozzle supply pressure, to achieve uniformity in flux distribution. The effect of these two compensating factors on a suggested measure of source performance quality is discussed below.

If, and only if, ample space exists between the skimmer and target (scattering test surface or scattering volume) it is usually desirable to introduce a separately pumped collimating chamber to remove any part of the gas flux through the collimator which does not participate in the scattering experiment. It should be noted that a collimator will not reduce the nonuniformity in flux distribution for Kantrowitz-Grey sources. Even if the collimator had a half angle (with respect to the nozzle exit) much smaller than the beam, thereby passing a very small central portion of the beam with little variation in flux intensity, at distances downstream from this collimator of the order of a the beam would again have a strongly nonuniform flux distribution. This penumbra or half shadow effect is also a result of beam divergence at the skimmer and has been discussed by others (e.g., Ref. 7). An additional collimator, with half-angle dimension (with respect to the nozzle exit) of the order of the skimmer dimension, should not affect the beam intensity or uniform flux distribution in the present nozzle source, since in case 3 the beam divergence at the skimmer is very small compared to the angular dimension of the beam.

Conditions for optimum performance of Kantrowtiz-Grey sources are commonly considered those under which the beam particle flux per steradian on the beam axis is maximized (in the absence of jet condensation) without regard to the form of the flux distribution over the beam cross section. Here instead, signal-to-noise ratio in scattering experiments is proposed as a measure of performance and estimates are made of the effect on performance if the sources of Refs. 7, 9, 13, 14 were operated not at maximum axial flux intensity but with nearly uniform flux distributions. In these estimates a collimating chamber is assumed to admit no effusive flow into the test chamber and a Gaussian is assumed to represent the roughly similar flux distributions at conditions for maximum axial beam flux intensities reported in Refs. 7 and 9. The flux distribution observed in this laboratory for operation under Kantrowitz-Grey source conditions, with a source modeled after Campargue,[8] is shown if Fig. 2 with the Gaussian fit described above, which represents the data quite well.

The reduction in axial flux intensity, $(\dot{n}_\Omega)_0$, necessary to convert from conditions for maximum $(\dot{n}_\Omega)_0$ to conditions for a nearly uniform flux distribution may be inferred from the argon beam measurements of Scoles and Torello,[14] who present measurements of $(\dot{n}_\Omega)_0$ vs nozzle-skimmer separation a, at several argon supply pressures. Their data indicate that if $(\dot{n}_\Omega)_0$ is reduced by a factor of four then $(\dot{n}_\Omega)_0$ is quite insensitive to a. This suggests weak scattering of jet gas by background gas in the test chamber and thus a uniform flux distribution.

In scattering experiments in which scattered gas at thermal energies is studied (e.g., the spatial distribution of particles reflected from a solid surface or differential scattering cross section between beam particles and a test gas) the signal strength is proportional to the total beam flux which takes part in the scattering process. However, these signals are often very weak, having magnitudes of the order of the detector noise associated with random discreet arrivals of background particles at the detector.[1,2] This noise is proportional to the square root of the density of background gas in the test chamber, and thus to the square root of the total particle flux through the source collimator. In such cases the information obtainable from the data is limited by the ratio (S/N) of the signal to this noise, thus (S/N) is an appropriate measure of source quality.

The useful portion of a beam with a gaussian flux distribution is chosen arbitrarily first to be within the cone on which the flux intensity has half its maximum (axis)value, then the cone of twice this half angle. The total useful beam flux is the integral of a gaussian over the solid angle within the cone of half maximum intensity:

$$\dot{N}_d = (\dot{n}_\Omega)_0 \cdot \Omega_b \cdot 0.752 \tag{1}$$

Ω_b is the useful beam solid angle, i.e., $\pi\theta_b^2$ and θ_b is the half angle of the cone on which $\dot{n}_\Omega = 0.5 \cdot (\dot{n}_\Omega)_0$. The total particle flux through the source collimator is the integral over the entire Gaussian flux distribution which is just twice the right hand side of Eq. (1). Accordingly

$$(S/N)_G \propto [(\dot{n}_\Omega)_0 \cdot \Omega_b \cdot (0.725)/2]^{1/2} \tag{2}$$

For nozzle source operation the total flux through the source collimator equals the total beam flux, thus

$$(S/N)_N \propto [(\dot{n}_\Omega)_0 \cdot \Omega_b]^{1/2} \tag{3}$$

Concluding from this discussion of measurements of Scoles and Torello that $(\dot{n}_\Omega)_0$ for a uniform flux distribution is one fourth of the maximum attainable value we obtain $(S/N)_N = 0.83 \cdot (S/N)_G$. Thus operation with a uniform flux distribution and operation at maximum $(\dot{n}_\Omega)_0$ are of almost equal quality by this measure. Furthermore, $(S/N)_N$ increases relative to $(S/N)_G$ when a larger portion of the gaussian beam is used. If beams with a half-angle of $2\theta_b$ are compared, $(S/N)_N \div (S/N)_G$ increases to 1.17.

3. Nozzle Beam Measurements

In this section measurements are reported of flux intensity and flux distribution as well as time-of-flight on the axes of argon beams generated with the nozzle source described in Sec. 1. The flux detector (discussed below) is an ionization gage with a constricted opening; the time-of-flight detector is discussed elsewhere.[15] The nozzle source has no separate collimating chamber, therefore a significant effusive flux of source chamber background gas enters with the beam through the source collimator opening.

3.1 Experimental

The test chamber, a stainless steel bell-jar, is pumped by a 6-in., liquid nitrogen baffled oil diffusion pump. The detector assembly is supported on a rotatable vertical shaft and angular positions in the horizontal plane are read from an externally mounted vernier dial. Pressure in the test chamber is measured with a Bayard-Alpert ionization gage, calibrated for argon. Test chamber pumping speed was determined to be 593 l/sec ± 10% for argon.

The nozzle, with a throat diameter of roughly 0.02 mm., was made from soft glass tubing, by drawing and fire-polishing the end. Although the nozzle has a diverging section after the throat, because of its arbitrary shape it is difficult to judge whether this produces an increase in the jet directivity over that of a simple converging nozzle. The distance from nozzle to source collimator a, can be varied from outside the vacuum system. A stainless steel disc (0.127 mm thickness) with an approximately square opening of the desired size for beam collimation is mounted over an opening in the wall of the welded stainless steel source chamber which is pumped by a liquid nitrogen baffled 6 inch diffusion pump. Argon supply pressures ranging from 0.5 to 8 atm are read from a Heise gage and are reproducible and constant to within 2%. The supply line passes through a frozen acetone cold trap. Measurements with a mass spectrometer located along the axis of the molecular beam showed that gaseous contamination in the beam was less than 200 ppm of argon.

Measurements of source flux intensity were made with an ionization gauge with a constricted opening, 1.0 mm wide by 2.00 mm high, (here called the flux detector). Time-of-flight measurements were made on the beam axis using the

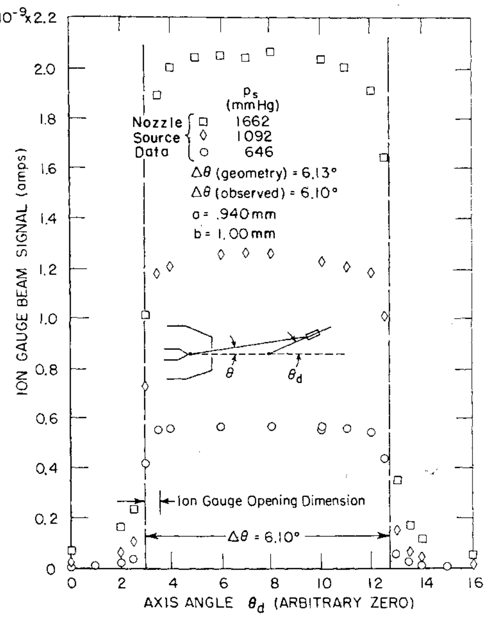

Fig. 3 Detector signal vs axis angle.

time-of-flight detector reported elsewhere.[15] These measurements were for two source collimator sizes, 1.00 mm and approximately 0.635 mm square. Angles read from the vernier on the centerline shaft, θ_d are related to angles with respect to the nozzle exit, θ, as sketched in Fig. 3.

The plate current of the flux detector was related to particle flux entering the detector by calibration against the calibrated test chamber ionization gage. Total particle flux into the test chamber $\dot{N}_t$ was determined from the test chamber ionization gauge signal and the known test chamber pumping speed. The beam flux per sterad $\dot{n}_\Omega$ was determined from the flux detector signal and the distance from the nozzle to the detector inlet. The ratio of total flux to directed beam flux into the test chamber $\dot{N}_t/\dot{N}_d$ was calculated from $\dot{N}_t$, $\dot{n}_\Omega$ and the geometrically determined beam solid angle dimension, i.e., b^2/a^2 where b is the edge dimension of the square source collimator. The ratio $\dot{N}_t/\dot{N}_d$ is larger than unity (observed values are of order 4.0) since the numerator is the sum of $\dot{N}_d$ plus the effusive flux of source chamber background gas through the source collimator. In signal-to-noise limited experiments, described in the previous section, (S/N) is proportional to $\dot{N}_d \div (\dot{N}_t)^{1/2}$, but data presented below for the nozzle source show both $\dot{N}_d$ and $\dot{N}_t$ are roughly proportional to the molecular beam solid angle; therefore, experimental values of (S/N) may be reduced to unit solid angle by dividing by the square root of this angle. (S/N) for a beam of unit solid angle is then

$$(S/N) = (\text{const})\cdot\dot{N}_d \div (\dot{N}_t\Omega_b)^{1/2} \quad (4)$$

Time-of-flight measurements were made on the axis of the beam to study the effect of supply pressure, nozzle collimator distance, and collimator size on speed distribution and mean speed. The time-of-flight detector and multichannel integration electronics are described elsewhere.[1,2,15,16] A description of the determination of speed distribution and mean speed from time-of-flight date is given elsewhere.[15] The speed distribution is defined as the rms spread in speed divided by the mean speed of particle flux in a differential solid angle of the beam

$$(SD) = \left[\int_0^\infty f(v)v^3(v - \bar{v})^2dv \div \int_0^\infty f(v)v^3dv\right]^{1/2} \div \bar{v} \quad (5)$$

where $f(v)$ is the particle distribution per volume in velocity and physical space, $\bar{v}$ is the mean speed of particle flux in a differential solid angle of the beam

$$\bar{v} = \int_0^\infty f(v)v^3vdv \div \int_0^\infty f(v)v^3dv \quad (6)$$

3.2 Experimental Results and Conclusions

Measurements of the beam particle flux per sterad vs distance normal to the molecular beam axis in the horizontal plane (called flux distribution) are presented as detector ion current vs detector axis angle θ_d (θ_d is related to θ in Fig. 3). In Fig. 2, flux distributions are shown for three values of the supply pressure, p_s = 1090, 2850, 5170 mm Hg, with a = 0.940 cm. These flux distributions are seen to be fairly uniform at moderate supply pressure and quite rounded at the highest pressure p_s = 5170 mm Hg. The width of the beam $\Delta\theta$ is defined as the angular width between points where the flux intensities are half their maximum values. Figure (2) shows that this width is very nearly constant, at fixed nozzle-collimator spacing, for any value of p_s considered. Also the measured value of $\Delta\theta$ = 3.82° is very nearly equal to the value calculated from geometry, $\Delta\theta = b/a$ = 3.87°. The geometric values are based on the deduction of Sec. 2 case 3 that the beam gas travels essentially radially outward from the nozzle exit. This very close agreement between observed and calculated $\Delta\theta$ may be fortuitous since method-of-characteristics solutions[17] for freejets show that the apparent origin for source flow which is approached asymptotically along the jet axis may be displaced from the nozzle exit plane by a distance of ten throat diameters or more, depending on exit conditions. An illustration of the uniform flux distributions for this nozzle source is shown in Fig. 3. These data were obtained at fairly low supply pressures and with the larger source collimator b = 1.00 mm. Also shown in this figure are the detector resolution, and the geometric and observed beam widths which again are in close agreement, and a sketch of the relation between θ and θ_d. Data of Figs. 2 and 3 were obtained with different detector filaments; consequently signals in Figs. 3 must be multiplied by a calibration factor of 1.9 before comparing them to Fig. 2.

Values of the four previously defined parameters $(\dot{n}_\Omega)_0$, $\dot{N}_t$, $\dot{N}_t/\dot{N}_d$, and (S/N) are plotted in Fig. 4 as functions of

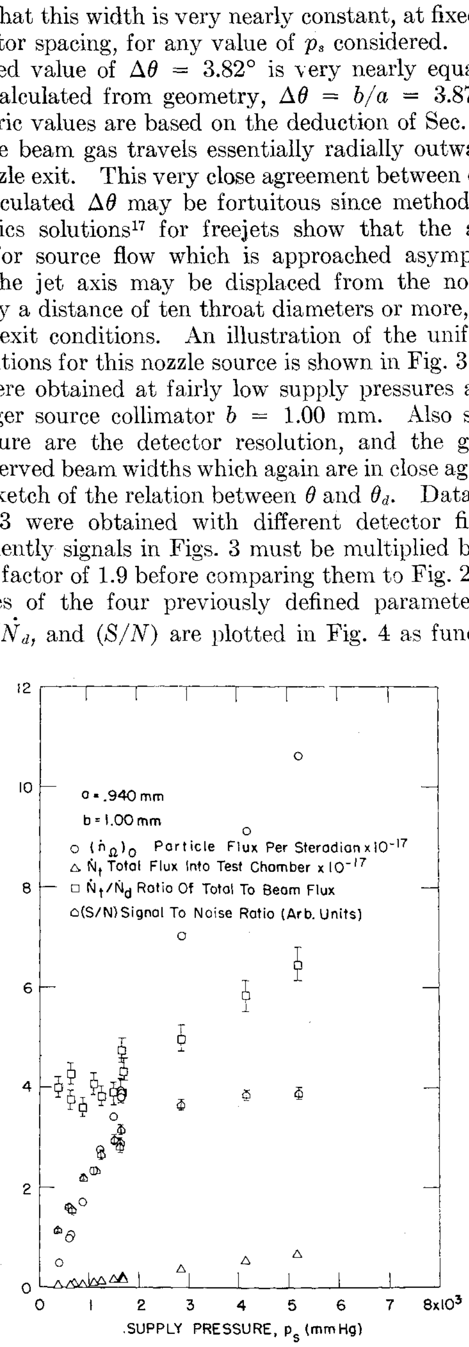

Fig. 4 Nozzle source performance vs nozzle supply pressure.

supply pressure p_s, with $a = 0.940$ cm and $b = 1.00$ mm, and in Fig. 5 as functions of nozzle-collimator spacing a, with $p_s = 2850$ mm Hg and $b = 0.635$ mm. In Fig. 4, $(\dot{n}_\Omega)_0$ rises rapidly over the whole range of p_s where measurements were taken, the highest value being 1.06×10^{18} particles/sterad sec; $\dot{N}_t$ shows an approximately linear rise; and $\dot{N}_t/\dot{N}_d$ also increases with increasing p_s, but not nearly so rapidly as $(\dot{n}_\Omega)_0$ or $\dot{N}_t$. (S/N), as defined by Eq. (4), shows a rapid initial rise with p_s but appears to approach a constant maximum value at fairly low values of p_s, where $(\dot{n}_\Omega)_0$ is still rising rapidly. This indicates that there is a wide range of supply pressures over which one can operate at nearly constant (S/N). These features, i.e., rapidly rising $(\dot{n}_\Omega)_0$ with p_s and an apparent leveling off of (S/N) at fairly low p_s, occurred also with the smaller source collimator opening of 0.635. "Error" bands in Figs. 4 and 5 are discussed below.

Figure 5 shows $(\dot{n}_\Omega)_0$, $\dot{N}_t/\dot{N}_d$ and (S/N) are quite insensitive to a over the range $0.2 \text{ cm} < a < 1.2$ cm., and consequently, $\dot{N}_t$ shows an a^{-2} dependence. These same features were observed in data not presented here for other supply pressures (1662 mm Hg, 5160 mm Hg) and with the larger (1.00 mm square) collimator. Hence the nozzle source may be operated at near optimum (S/N) over a fairly broad range of nozzle collimator spacings a and collimator dimensions b. Consequently, the dimensions (a,b) may be conveniently elected to produce a molecular beam of desired dimensions with no resultant loss in signal-to-noise ratio.

The data in Fig. 5 show a roughly a^{-2} variation for both $\dot{N}_t$ and $\dot{N}_d$, and the effusive contribution to $\dot{N}_t$ is appreciably larger than the directed beam contribution. However, the explanation given previously for the origin of the nondirected, i.e., effusive, contribution to $\dot{N}_t$ would imply that it was insensitive to a. After a careful review of experimental errors the author feels that accumulated errors are not nearly large enough to explain this apparent anomaly. Large errors in the parameters $\dot{N}_t/\dot{N}_d$ and (S/N) presented in Figs. 4 and 5 may result from the assumption that the directed beam appears as source flow originating at the nozzle exit, since, as mentioned above, the apparent origin may be ten diameters or more away from the nozzle exit. To assess the effects of such an error on these parameters it was assumed that the origin of source flow is known only to within $\pm$ 0.25 mm (this is effectively an error in a). This error would affect only those parameters which depend upon a through a geometrically determined beam solid angle i.e., $\dot{N}_t/\dot{N}_d$ and (S/N) and the resulting error bands are included in Figs. 4 and 5. Although this error would strongly affect the results for small values of a it is not large enough to explain the apparent anomaly cited above.

Mean speed $\bar{v}$ [Eq. (6)] along the beam axis was found to be insensitive to p_s, a or b. The speed distribution [Eq. (5)] was found to be independent of a or b but showed a dependence on supply pressure as given in Table 1. These are mean values obtained from data with a mean scatter of $\pm 10\%$. The rise in speed distribution with decreasing p_s is presumably due to translational freezing occurring nearer to the nozzle exit, i.e., at a lower Mach number. It is shown in Ref. 15 that speed distribution is related to the jet Mach number at transition M_t, if one assumes that transition does not affect the velocity distribution, as

$$M_t^{-1} = (SD)(\gamma)^{1/2} \quad (7)$$

where γ is the specific heat ratio. A speed distribution of 0.1 in an argon molecular beam thus corresponds to $M_t = 7.75$.

Table 1 Speed distribution vs supply pressure

p_s (mm Hg)	646	1665	4140	5170
(SD)	0.143	0.112	0.084	0.098

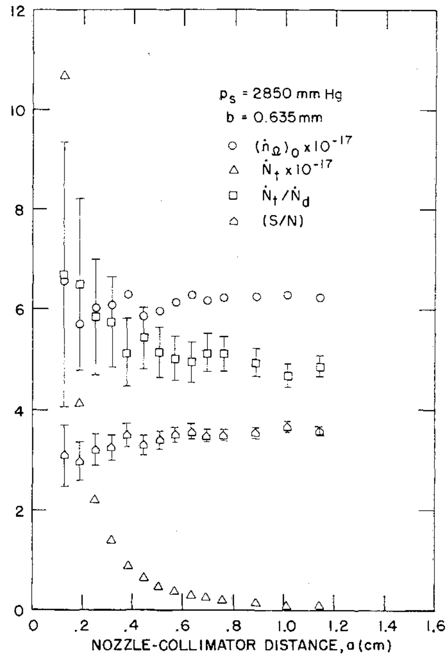

Fig. 5 Nozzle source performance vs nozzle-collimator distance.

4. Comparison of the Nozzle Source with a Kantrowitz-Grey Source

A Kantrowitz-Grey source was built in this laboratory based on a design by Campargue.[8] The performance of this source[18] was compared to that of the nozzle source using the same vacuum system and the same flux detector that was just described. The dimensions of the Kantrowitz-Grey source are: nozzle exit diameter = 0.25 mm, skimmer diameter = 0.74 mm, collimator diameter = 1.02 mm, skimmer to collimator = 12.0 mm (nozzle to skimmer distance a is variable).

Variation in the flux intensity with axis angle is shown in Fig. 2 for operating conditions which produced the maximum flux intensity on the beam axis; these are $p_s = 88$ mm Hg and $a = 2.03$ mm. For these operating conditions $(\dot{n}_\Omega)_0$ and $\dot{N}_t$ were determined as described in Sec. 3.1. The total beam flux $\dot{N}_d$ for this approximately Gaussian flux distribution, within the cone of half maximum intensity, is Eq. (1), and from Fig. 2 $\theta_b = 4.2°$. (S/N) for a beam of unit solid angle may be obtained from these source measurements only if one assumes that $\dot{N}_t \propto \dot{N}_d$ with changing beam solid angle. There results

$$(\dot{n}_\Omega)_0 = 1.42 \times 10^{18} \text{ particles/sterad sec}$$
$$\dot{N}_t = 4.03 \times 10^{16} \text{ particles/sec} \quad (8)$$
$$\dot{N}_t/\dot{N}_d = 9.25 \qquad (S/N)_G = \text{const } 3.34$$

Flux distributions for the nozzle source may be approximated by a square wave for all data shown in Fig. 3. The data for $p_s = 1662$ mm Hg in Fig. 3 have a maximum signal of approximately one-fourth the maximum Kantrowitz-Grey source signal in Fig. 2. (Recall that data in Fig. 3 must be multiplied by 1.9 for comparison.) This is the same reduction factor for flux intensity used for the comparison of Sec. 3. Nozzle source operating conditions corresponding to these data yield

$$(\dot{n}_\Omega)_0 = 3.8 \times 10^{17} \text{ particles/sterad sec}$$
$$\dot{N}_t = 1.75 \times 10^{16} \text{ particles/sec} \quad (9)$$
$$\dot{N}_t/\dot{N}_d = 4.33 \qquad (S/N)_N = \text{const } 3.06$$

The effusive contribution to $\dot{N}_t$ is seen to be large compared to the directed flux, $\dot{N}_d$, not only for the nozzle source but also for the Kantrowitz-Grey source, even though the Kantrowitz-Grey source has an additional collimating chamber. Apparently this is caused by high background pressure in the collimating chamber resulting from high impedance to flow between the collimator and the pump.

Using signal-to-noise ratio, defined by Eq. (4), as a measure of source performance the Kantrowitz-Grey source and the nozzle source are of comparable quality by Eqs. (8) and (9): $(S/N)_N \div (S/N)_G = 0.91$.

Appendix: Proposed Nozzle Source Collimator

The uniform flux distribution of the nozzle source, Fig. 3, suggests a unique means of preventing the effusive flow of source chamber background gas into the test chamber. Bauer[19] recently suggested that this collimation, which is usually achieved by a separately pumped collimating chamber located between source and test chambers, be achieved instead by replacing the orifice in Fig. 1 by a channel with length, l, along the beam axis, large compared to a typical lateral dimension, b, and with a conically diverging cross section forming a constant solid angle with respect to the nozzle exit equal to the beam dimension. The directed beam, due to its small divergence, would suffer no appreciable attenuation by collisions of particles with the channel wall. The ambient gas density in the channel would be greatest at the inlet, equal to source chamber ambient density. Thus, since these data indicate the jet gas has suffered very little attenuation over the distance, a, from the nozzle to the collimating orifice, and since the length of the channel which would replace this orifice is at most of order a, one may expect negligible attenuation of the directed beam by ambient gas in the channel. As an example consider a molecular beam with a circular cross section and a half-angle of 0.025 rad ($\simeq 1\frac{1}{2}°$). If the collimating orifice of diameter b is replaced by a conically diverging channel with inlet diameter b and length $10b$, then from tabulations of Clausing's factor for parallel channel flow in Dushman,[20] the flow of source chamber ambient gas into the test chamber would be reduced by a factor of roughly 0.36. The effectiveness of this collimation would increase with decreasing beam angle and viceversa, e.g., for a beam half-angle of 0.05 rad ($\simeq 3°$) and $l = 10b$ the reduction factor would be only 0.58.

The proposed method of beam collimation cannot be applied to existing Kantrowitz-Grey sources operating a maximum axial flux intensity. Beam divergence at the skimmer is of the order of the beam half angle dimension; consequently if this channel replaced the skimmer a substantial fraction of the admitted beam particles would collide with the channel walls. At conditions for maximum axial flux, particles at the skimmer inlet moving perpendicular to the beam axis have a mean free path, even for large angle deflections, which is at most of order ten times the skimmer (or replacement channel) inlet diameter. (eg., At maximum argon axial flux in Ref. 7 this mean free path is $\simeq$20 mm compared to the skimmer diameter of 1.0 mm.). Consequently in a channel with length much greater than inlet diameter the substantial fraction of beam particles scattered from the channel walls would severely attenuate, through gas-gas collisions, the remaining beam portion.

This collimation scheme will be tested in a nozzle molecular beam source presently being designed in this laboratory.

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