STUDIES OF SUPERSONIC BEAM FORMATION AT LOW TEMPERATURES FOR A POLARIZED HELIUM 3 ION SOURCE

by

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ABSTRACT

The formation of a molecular beam using a miniature supersonic nozzle source is discussed.

The results of operation at room, liquid nitrogen and liquid helium temperatures of a supersonic nozzle system designed for use in a polarized helium\(^3\) ion source are presented. It is shown that helium\(^4\) beam intensities at 4,20\(^\circ\)K are approximately 1/8 of those at 300\(^\circ\)K. Factors upon which the beam intensity depend have been investigated experimentally and it is found that at room temperature and a distance of 16cm from the skimmer a helium\(^4\) beam intensity of 3x10\(^{16}\) molecules/cm\(^2\)/sec is attainable under certain circumstances.

This beam intensity is an improvement by a factor of 10 over the original performance of the nozzle source.

Assuming a 40% transmission through the magnet and a 0.25% ionization efficiency an ion current of 0.02 microamperes is estimated for the polarized helium\(^3\) ion source.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>CHAPTER I</th>
<th>INTRODUCTION</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHAPTER II</td>
<td>SUPERSONIC MOLECULAR BEAM FORMATION</td>
<td>2</td>
</tr>
<tr>
<td>A. Fundamental Concepts</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>B. Summary of Kantrowitz and Grey's Original Theory</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>C. Review of Existing Experimental Results</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>D. The Nature of the Expanding Beam</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>E. Interaction with the Skimmer</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>CHAPTER III</td>
<td>THE POLARIZED BEAM APPARATUS</td>
<td>15</td>
</tr>
<tr>
<td>A. General Introduction</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>B. The Low Temperature Beam Source</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>C. Testing of the Nozzle-Skimmer-Collimator System</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>D. Analysis of the Experimental Results</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>CHAPTER IV</td>
<td>INVESTIGATIONS INTO FACTORS AFFECTING BEAM INTENSITY</td>
<td>21</td>
</tr>
<tr>
<td>A. Nozzle-Skimmer Separation</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>B. Mechanical Alignment</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>C. Effect of Skimmer Diameter and Manufacture</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>1. Skimmer Diameter</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>2. Skimmer Manufacture</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>D. Presence of Collimator</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>E. Background Gas Pressure</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>F. Nozzles</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>G. Summary</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td></td>
<td>List of Tables</td>
<td>Page</td>
</tr>
<tr>
<td>---</td>
<td>-------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>1</td>
<td>Dimensions of Supersonic Beam System</td>
<td>16</td>
</tr>
<tr>
<td>2</td>
<td>Selected Physical Parameters</td>
<td>19</td>
</tr>
<tr>
<td>3</td>
<td>Selected Experimental and Corresponding</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Theoretical Beam Intensities</td>
<td>follows p.19</td>
</tr>
<tr>
<td>4</td>
<td>Terminal Mach Numbers</td>
<td>28</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

To follow page

1. The Regimes of Gas Dynamics .......................... 4
2. Schematic of Proposed Molecular Beam Source .......................... in text p. 5
3. An Idealized Laval Nozzle ........................................ in text p. 6
4. The Temperature Ratio $T_1/T_0$ as a Function of the Mach Number M ........................................ 7
5. The Pressure Ratio $P_1/P_0$ as a Function of the Mach Number M ........................................ 7
6. The Velocity of Mass Motion $W$ and the Most Probable Particle Velocity $U$ as a Function of the Mach number for a Laval Nozzle Temperature of 2.2° K .......................... 7
7. Relative Transmission of He$^3$ Particles Through the Skimmer and Collimator as a Function of Mach number .......................... 8
8. Relative Transmission of He$^3$ particles Through the Nozzle, Skimmer and Collimator as a Function of the Mach Number ........................................ 8
9. Typical Supersonic Molecular Beam Performance for Nitrogen ........................................ 9
10. Schematic Representation of Flow from an Orifice into an Evacuated Region ........................................ in text p. 10
11. Distribution of Mach Number along the Axis of Symmetry of the Expanding Jet ........................................ 11
12. Impact Pressure Downstream of the Orifice .......................... 12
13. Correlation of Asymptotic Axial Mach Numbers for Argon, Neon and Helium Jets ........................................ 12
14. Ratio of Observed to Theoretical Intensity as a Function of Knudsen Number / Mach Number based on Free Stream Conditions ....................................................... 13

15. Shock at the Skimmer. .................................................. 13

16. Schematic Diagram Showing the Arrangement of the Components of the Polarized He\(^3\) Ion Source ........................................ 15

17. The Low Temperature He\(^3\) Atomic Beam Source. .......... 15

18. Detail of Nozzle Assembly ............................................ 15

19. The Magnet Assembly .................................................. 17

20. Block Diagram of Beam Detection System. ................. in text p. 18

21. Typical Chart Recording ............................................. in text p. 18

22. The Dependence of Beam Intensity on Temperature .... 18

23. The Ratio of Experimental to Theoretical Beam Intensities as a Function of Knudsen Number to Mach Number .. 19

24. Adjustable Nozzle-Skimmer Apparatus ......................... 21

25. Turning Mechanism for Adjustable Nozzle-Skimmer Apparatus 21

26. Typical Results obtained from Adjustable Nozzle-Skimmer Apparatus ................................................................. 22

27. Typical Results Obtained for Fixed Nozzle-Skimmer Separation. ................................................................. 22

28. Beam Intensity Results at 77° K. ............................. 23

29. Beam Intensity Results at 300° K. ............................. 23

30. Beam Intensity Results at 300° K. ............................. 23

31. Correspondence between Nozzle and Nozzle-Skimmer Pressures at 300° K. ....................................................... 23
32. Correspondence between Nozzle and Nozzle-Skimmer Pressure at 77° K. .................................. 23
33. Alignment Assembly ........................................... 24
34. Typical Results showing Effect of Poor Alignment. .......................... 24
35. Skimmer Manufacture ............................................. 26
36. Pumping System for Nozzle-Skimmer Region ................................ 26
37. Beam Intensity Dependence on Background Gas Pressure .................. 29
38. Beam Intensity Dependence on Background Gas Pressure .................. 29
39. Beam Intensity Dependence on Background Gas Pressure .................. 29
40. Beam Intensity Dependence on Background Gas Pressure .................. 29
41. Beam Intensity Dependence on Background Gas Pressure .................. 29
42. Performance of 0.005" Tubing Nozzle .................................. 30
43. Performance of 0.0095" Tubing Nozzle .................................. 30
44. Performance of 0.020" Nozzle ........................................... 30
45. Room Temperature Intensities for 0.0095" Tubing ......................... 31
46. Room Temperature Intensities for 0.0095" Tubing ......................... 31
47. Liquid Nitrogen Temperature Intensities for 0.0095" Tubing .............. 31
48. Bundle of Capillaries used as a Nozzle ..................................... 31
49. Geometrical Arrangement of Multiple Capillary Device .................... 31
50. Performance of Multiple Capillary Device .................................... 31
51. Comparison of Beam Intensities .......................................... 33
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CHAPTER I

Introduction

Miniature supersonic nozzle systems have been shown to produce high intensity molecular beams. These beams besides being studied because of their own interesting properties have been used by various experimenters to investigate surface scattering, thermal relaxation, separation of gas mixtures, condensation phenomena, molecule-molecule collisions and many other physical phenomena. We need these intense beams for the successful operation of our polarized helium$^3$ ion source.

Initial sections of this thesis will introduce some of the concepts used in discussing the gas dynamics of nozzle systems and then will briefly review the original theoretical treatment of miniature supersonic nozzle systems. A summary of experimental results obtained by various investigators will be presented along with a picture of the expansion process as it is now understood. The nature of the skimmer interaction which limits the beam intensity will be reviewed.

With the above as background, we will briefly discuss the polarized He$^3$ beam apparatus whose initial design and construction has been reported by Axen (Ax 65) and then report on the performance of the supersonic nozzle system (shown schematically in figure 2) which forms an important part of this apparatus.

Later sections will consider the experimental investigations into the nature of the beam expansion as required in light of these preliminary results.

The last section will estimate the beam intensity one might hope to obtain from our polarized beam apparatus based on experimental results discussed in other parts of this thesis.
CHAPTER II
Supersonic Molecular Beam Formation

A. Fundamental Concepts

In order to provide a basis for the discussion of nozzle systems it will be useful to define a number of common terms. These terms include the characteristic length, boundary layer, free steam, Reynolds number, Knudsen number, Mach number, subsonic flow, transonic flow, supersonic flow, hypersonic flow, free molecular flow, transition flow, slip flow and continuum flow.

Many dimensionless parameters make use of a characteristic length. This length may be simply related to the physical size of the object through which or around which gas flow occurs. For example, the dimension could be the diameter of a sphere or a piece of pipe. Under certain circumstances, however, the significant characteristic dimension is often the boundary layer thickness.

Often in flow over an object a velocity gradient perpendicular to the surface of the object is set up. The velocity starts at zero at the surface and rapidly approaches a constant value. The region where the large velocity gradient exists is known as the boundary layer while the region where the velocity gradient is zero is known as the free stream.

In gas or fluid dynamics it has been found that certain parameters are useful in describing the characteristics of flow experienced under varying conditions of pressure, temperature, velocity etc. The three common dimensionless numbers, namely: The Reynolds number\(^1\) (Re), the Knudsen number (Kn), and the Mach number (M), are defined as follows:

\(^1\)Historical note: Reynolds while investigating fluid flow through similar pipes found that a critical value of this parameter predicted the onset of turbulent flow for varying flows, fluids and diameters of pipes.
Reynolds number \( = Re = \frac{V \rho d}{\nu} \) \hspace{1cm} (1)

Mach number \( = M = \frac{V}{a} \) \hspace{1cm} (2)

Knudsen number \( = Kn = \frac{\lambda}{d} \) \hspace{1cm} (3)

Where \( V \) = Particle velocity

\( \rho \) = Gas density

\( \nu \) = Viscosity

\( a \) = Velocity of sound

\( d \) = Characteristic length

\( \lambda \) = Molecular mean free path

In a great deal of work connected with gas flow through supersonic nozzles the ratio \( Kn/M \) is used as a parameter. This number can be related to the Reynolds number using a relation derived from kinetic theory (see for example Kennard (Ke 38))

\[ V = \frac{1}{2} \rho \lambda a \sqrt{\frac{8}{\pi \gamma}} \] \hspace{1cm} (4)

Where \( \gamma \) = Ratio of specific heats.

Substituting (4) into (1) and using (2) and (3) one obtains:

\[ \frac{Kn}{M} = \frac{1}{Re} \left( \frac{\pi \gamma}{2} \right)^{1/2} \] \hspace{1cm} (5)

Under most circumstances \( \gamma \) is a constant so essentially \( Kn/M \) is simply an inverse Reynolds number.

Two common schemes for the classification of flow problems are presented below:

The first, based solely on the Mach number, is as follows: The flow is described as subsonic if the fluid or gas velocity is less than the speed of sound in the medium \( (M < 1) \), transonic when the fluid or gas velocity is comparable with the sound speed \( (M \sim 1) \), supersonic when the fluid or gas velocity exceeds the sound speed \( (M > 1) \), and hypersonic when the fluid or gas
velocity is much larger than the sound speed \((M > 1)\).

The other scheme uses both the Mach and Reynolds numbers to define four flow regimes. Within each of these regimes the characteristics of the flow can be described by one predominate mechanism. The flow regime appropriate to a particular situation can be conveniently identified by the values of the Mach and Reynolds number. These two numbers are used in figure 1 to characterize the flow regimes which one usually refers to as free molecular, transition, slip and continuum flow.

To give a simple physical picture of the meaning of the various flow regimes consider the mean free path in the gas. For free molecular flow the mean free path is much greater than the characteristic body length and thus molecules reemitted from a body surface do not collide with free stream molecules until far away from the body. For the transition regime the mean free path is about equal to the typical body dimension. Here surface collisions and free stream intermolecular collisions occur with equal frequency. For slip flow the mean free path is typically 1 to 10\% of the boundary layer thickness or other characteristic dimension of the object. For continuum flow the characteristic length greatly exceeds the mean free path and thus free stream intermolecular collisions predominate over surface collisions. For continuum flow, the gas immediately next to a body is essentially at rest, whereas in slip flow the layer of gas immediately adjacent to the solid is no longer at rest but has a finite tangential velocity.

Rarefied gas dynamics refers collectively to the free molecular, transition and slip flow regimes.
Figure 1. The Regimes of Gas Dynamics
B. Summary of Kantrowitz and Grey's original theory

When Kantrowitz and Grey (Ka 51) proposed the use of a miniature supersonic Laval nozzle for a molecular beam source, they visualized a system consisting of a nozzle, skimmer, and collimator as shown schematically in figure 2. Their theoretical treatment of this system was modified slightly by Parker et al (Pa 60) and a summary of the combined treatment is presented below.

Three critical assumptions are made:

1. The flow along the axis of the supersonic jet up to the skimmer entrance is isentropic and may be treated by the methods of continuum gas dynamics.

2. The skimmer samples an undisturbed portion of the isentropic core.

3. Collisions between molecules downstream of the skimmer may be neglected.
With these conditions in mind we can proceed in the derivation of what is often referred to as the "theoretical beam intensity."

An idealized version of a converging-diverging nozzle is shown in figure 3. The mass flow through such a supersonic nozzle operating under isentropic flow conditions is given by Shapiro (Sh 53) as

$$ G = A^* \left( \frac{2}{\gamma + 1} \right)^{\frac{1}{2 - 1}} \sqrt{\frac{2 \mu}{R}} \frac{\gamma}{\gamma + 1} \frac{P_0}{\sqrt{T_0}} $$

where:
- $G$ = Flow in mass/unit time
- $A^*$ = Cross sectional area of nozzle throat
- $\mu$ = Molar mass
- $R$ = Molar gas constant
- $P_0$ = Pressure at nozzle entrance
- $T_0$ = Temperature at nozzle entrance

and the velocity distribution in the $Z$ direction, along the beam, is given by

$$ f(U) = \frac{m}{\sqrt{2 \pi k T_i}} e^{-\frac{m (U-W)^2}{2 k T_i}} $$

where:
- $U$ = Particle velocity in $Z$ direction
- $m$ = Particle mass
\[ k = \text{Boltzman's constant} \]

\[ T_1 = \text{Internal temperature of gas} \]

\[ W = \text{Average forward velocity of the particles (velocity of mass motion in the } Z \text{ direction)} \]

\[ W = \sqrt{\frac{8 RT_0 M^2}{\mu (1 + \frac{\gamma - 1}{2} M^2)}} \]

\( f(u) \) represents the number of particles with velocities between \( U \) and \( U + du \) normalized so that

\[ \int_{-\infty}^{\infty} f(u) du = 1 \]

The usual Maxwellian velocity distribution is a special case of the above distribution when \( W = 0 \).

Other physical properties of the flow through an idealized Laval nozzle can be described by the ratio \( \frac{T_1}{T_0} \), the ratio \( \frac{P_i}{P_0} \), the velocity of mass motion (\( W \)), and the most probable particle velocity (\( \bar{U} \)) as a function of the Mach number. These have been presented graphically for \( \gamma = 1.66 \) in figures 4, 5, and 6. \( T_1 \) and \( P_1 \) are the internal temperature and pressure of the beam, i.e. the temperature and pressure of the gas molecules with respect to a coordinate system moving with the beam. The Mach number, \( M \), is defined as \( M = \frac{W}{a} \) where \( W \) is the velocity of mass motion of the beam and \( a \) is the velocity of sound at pressure \( P_1 \) and \( T_1 \).

When one takes the skimmer and collimator into account the flow through the collimator in atoms per second is given by

\[ F_2 = \frac{N_1 S_2 a_0}{2\pi D^2} \left\{ \frac{\gamma M^2}{2} \left(1 + \frac{\gamma - 1}{2} \frac{M^2}{2} \right) + \sqrt{\frac{\gamma M^2}{2} + 1} \right\} \]

where:

\[ N_1 = \text{Density of particles per unit volume at the skimmer entrance} \]

\[ S_1 = \text{Area of skimmer aperture} \]
Figure 4. The Temperature Ratio $\frac{T_1}{T_0}$ as a Function of the Mach Number $M$

Figure 5. The Pressure Ratio $\frac{P_1}{P_0}$ as a Function of the Mach Number $M$
Figure 6. The Velocity of Mass Motion $W$ and the Most Probable Particle Velocity $U$ as a Function of the Mach Number for a Laval Nozzle Temperature of $2.2^\circ K$ (for He gas)
\[ S_2 = \text{Area of collimator aperture} \]
\[ D = \text{Distance from skimmer to collimator} \]
\[ a_0 = \text{Velocity of sound at nozzle entrance} \]
\[ M = \text{Mach number of beam} = \frac{W}{a} \]
\[ \text{erf} = \text{Error function} \]

For \( M > 3 \) this expression is given approximately by

\[ F_2 = \frac{N_1 S_1 S_2 a_0}{2 \pi D^2} \frac{M \left( \frac{3}{2} + \gamma M^2 \right)}{\sqrt{1 + \left( \frac{\gamma - 1}{2} \right) M^2}} \] (9)

It might be pointed out that the Mach number used is that which characterizes the beam flow at the skimmer entrance. For a fixed density \( N_1 \) and geometrical constants fixed in equation 9 one can write a transmission function

\[ F_2 \left( \frac{2 \pi D^2}{N_0 S_1 S_2 a_0} \right) = \frac{M \left( \frac{3}{2} + \gamma M^2 \right) (1 + \text{erf} \sqrt{\frac{\gamma M^2}{2}})}{\sqrt{1 + \left( \frac{\gamma - 1}{2} \right) M^2}} + \frac{1}{2 \pi \sqrt{2 + \gamma M^2}} e^{-\frac{\gamma M^2}{2}} \] (10)

This function is plotted in figure 7 and increases roughly as \( M^2 \). The density \( N_1 \), however, is also a function of the Mach number

\[ \frac{N_1}{N_0} = \frac{1}{\sqrt{1 + \frac{\gamma - 1}{2} M^2 \frac{3}{\gamma - 1}}} \] (11)

where \( N_0 = \text{density of particles behind the nozzle} \).

Substituting this expression in equation 10 the transmission function for the flow through the nozzle, skimmer and collimator becomes

\[ F_2 \left( \frac{2 \pi D^2}{N_0 S_1 S_2 a_0} \right) = \left\{ \frac{M \left( \frac{3}{2} + \gamma M^2 \right) (1 + \text{erf} \sqrt{\frac{\gamma M^2}{2}})}{\sqrt{1 + \left( \frac{\gamma - 1}{2} \right) M^2}} + \frac{1}{2 \pi \sqrt{2 + \gamma M^2}} e^{-\frac{\gamma M^2}{2}} \right\} \] (12)

This transmission function plotted in figure 8 shows a broad maximum about \( M = 2.5 \). Thus for a given flow through the nozzle it appears as if the best transmission would be obtained with low Mach numbers.

It is unfortunately only in special cases that it is possible to fulfil the requirements mentioned at the beginning of this section; thus under most
Figure 7. Relative Transmission of He$^3$ Particles Through the Skimmer and Collimator as a Function of the Mach Number

Figure 8. Relative Transmission of He$^3$ Particles Through the Nozzle, Skimmer and Collimator as a Function of the Mach Number
circumstances one would not expect the Kantrowitz-Grey predictions to be fulfilled but they serve as a useful guideline in assessing the performance of a nozzle beam system. In subsequent sections we shall discuss why the assumptions made at the beginning of this section are not in general true and how these changes affect the molecular beam formation.

C. Review of existing experimental results

Perhaps the most instructive way to illustrate how practical supersonic nozzle beams vary from the ideal Kantrowitz-Grey picture is to illustrate some sample experimental results. The most revealing of all experimental data presentations is the dependence of beam intensity on the nozzle-skimmer distance. This dependence along with the dependence expected from Kantrowitz and Grey's theory is shown in figure 9 (after Fenn and Deckers (Fe 63)). It is clear the actual experimental results do not follow the predictions of Kantrowitz and Grey.

The experimental curves can in general be divided into 3 regions:

1. For short nozzle-skimmer distance the beam flux decreases with increasing nozzle-skimmer separation until a minimum occurs.
2. At larger nozzle-skimmer separations the beam flux increases until a maximum is reached.
3. Further increases result in a decrease in beam flux.

One might point out that the three regions described above correspond roughly to flow regimes at the skimmer which are:

1. Continuum
2. Slip-transition
3. Free-molecular

Needless to say the appearance of these 3 regions and the fact that the beam intensities in many cases were substantially lower than predicted
Figure 9. Typical Supersonic Molecular Beam Performance for Nitrogen
by the theory of Kantrowitz and Grey led people to examine the true nature of the supersonic jet they had produced. In the following section the nature of the expanding jet and its interaction with the skimmer is considered with a view to explaining the experimental results presented here.

D. The nature of the expanding beam

The flow from a nozzle or hole into an evacuated region is shown schematically in figure 10. The gas passing through the nozzle opening expands isentropically in a free jet unaffected by the background gas outside the jet boundary. This expansion has been described theoretically for $\gamma = 1.4$ by Owen and Thornhill (Ow 52) using the method of characteristics.
and confirmed experimentally by Reiss (Fe 63) and Sherman (Sh 63). Their solution is applicable to any jet, flowing into any external pressure, in that region bounded by the orifice and the first wavefront which registers the existence of an external pressure outside the jet. Ashkenas and Sherman (As 66) have extended Owen and Thornhill's solution to gases with $\gamma = 1.67$ (e.g. Helium). They suggest the following fitting formula for the centerline Mach number of a free jet:

$$M = A \left( \frac{x-x_0}{d} \right)^{\gamma-1} - \left( \frac{\frac{1}{2} \left( \frac{\gamma+1}{\gamma-1} \right)}{A \left( \frac{x-x_0}{d} \right)^{\gamma-1}} \right) + C \left( \frac{x-x_0}{d} \right)^{-3(\gamma-1)} \quad (13)$$

where

- $x =$ distance from orifice along centerline
- $d =$ diameter of orifice
- $\gamma =$ Ratio of Specific Heats
- $A$, $C$, and $X_0$ are fitting constants

for $\gamma = 1.67; \ A = 3.26, \ C = 0.31, \ \frac{X_0}{d} = 0.075$

This three term formula is accurate for $X > d$ with maximum deviations from the characteristic data of $\frac{1}{2} \%$ of $M$. The calculated values are shown graphically in figure 11. Another important parameter to know is the impact pressure as a function of distance downstream from the orifice. This is the pressure one obtains experimentally upon inserting a Pitot tube, a small diameter piece of tubing with a pressure gauge attached to one end, into the beam so the open end of the tube points upstream. This pressure is essentially $\rho V^2$ where $\rho$ is the gas density at the entrance to the Pitot tube and $V$ is the particle velocity. Ashkenas and Sherman give the ratio of impact pressure to source pressure as a function of distance downstream from the orifice by means of the following fitting formula:
Figure 11. Distribution of Mach Number Along the Axis of Symmetry of the Expanding Jet
where $P_i$ = impact pressure

$P_o$ = pressure behind orifice

$X_0'$ and $A$ are fitting parameters

for $\gamma = 1.67$; $\frac{X_0'}{d} = 0.04$, $A = 3.26$

This formula which gives 1% or better predictions of the characteristic data for $\frac{X}{d} \geq 2.5$ is shown graphically in figure 12.

The previous results are valid only until the expanding jet becomes aware of the background pressure. At this point, the Mach disk, the transition from isentropic continuum flow to nonisentropic free molecular flow occurs. A consequence of this transition is the "freezing" of the thermal velocity and thus the Mach number. This terminal Mach number has been found by Anderson et al (An 65) and Abuaf et al (Ab 66) to obey in general the following relationship

$$M_T = 1.17 \left( \frac{1-\gamma}{\gamma} \right)^{\frac{1}{3}}$$

where $Kn_o$ is the ratio of viscosity-based mean free path in the nozzle stagnation chamber, that region upstream of the nozzle opening, to the nozzle diameter. Abuaf et al (Ab 66) have found, however, that this formula overestimates the terminal Mach number in the case of helium. Their results for helium and other gases are shown in figure 13.

Once the transition to free molecular flow has occurred the beam intensity, although continuing to vary inversely with the distance squared from the nozzle, is now scattered in accordance with the usual attenuation factor (Ra 56)
Figure 12. Impact Pressure Downstream of the Orifice
Figure 13. Correlation of Asymptotic Axial Mach Numbers for Argon, Neon and Helium Jets
where \( \lambda_v \) = mean free path for a beam molecule of velocity \( V \)
\( l \) = length of chamber

E. Interaction with the skimmer

The expansion of the jet up to the skimmer is fairly well understood and one might be led to believe that a part of this promising jet could be skimmed off for use as a small narrowly collimated intense molecular beam. The skimmer, however, interacts with this beam and reduces, in some cases, the intensity to levels obtainable with a simple oven beam. In this case the skimmer acts as the orifice and the nozzle-skimmer region acts as an oven.

Fenn and Deckers (Fe 63) have correlated the ratio of observed flow through the skimmer to the theoretical flow predicted by Kantrowitz and Grey with the dimensionless parameter \( Kn/M \) (the ratio of Knudsen number based on skimmer diameter and free stream mean free path at the skimmer entrance to the free stream Mach number determined using the Owen-Thornhill solution). This correlation, which has been confirmed by other groups, is presented (for nitrogen) in figure 14. Figure 14 includes the data of Fenn and Deckers (Fe 63) shown in figure 9. They have proposed a mechanism to explain, at least qualitatively, the shape of the curves obtained. Consider as in figure 15 a normal shock in front of the skimmer with \( M_1, \rho_1 \), and \( T_1 \) representing the Mach number, gas density, and temperature of the beam under free stream conditions. Free stream conditions are those that exist in the region sufficiently far in front of the skimmer so that the beam
Figure 14. Ratio of Observed to Theoretical Intensity as a Function of Knudsen Number Over Mach Number Based on Free Stream Conditions. Open Points are from Penn and Deckers for Nitrogen at Nozzle Pressures of 100 Torr (Triangles), 50 Torr (Circles), and 10 Torr (Squares) with a 1.6mm Skimmer. Crossed Points are for Various Pressures with 0.4mm Skimmer. Solid Points are for Nitrogen from Scott and Drewry. The Single Square Solid Point is for Hydrogen from Becker and Biers Data.
particles are unaware of the skimmer's existence. As the beam passes through the shock region its properties are changed so that at the skimmer inlet they are better represented by $M_2$, $\rho_2$, and $T_2$. The degree to which these properties are changed determines how much the beam is attenuated from the "theoretical beam intensity" which assumes free stream conditions at the skimmer inlet. As the gas density in front of the skimmer is decreased, the shock wave becomes thicker and the skimmer inlet is penetrated further and further by the shock zone. Thus the gas actually entering the skimmer becomes less and less "shocked" until finally at low enough densities the gas entering the skimmer is in the free stream condition. In figure 14 we see that as $\frac{Kn}{M}$ or $\frac{1}{Re}$ increases and thus free stream conditions are approached the intensity approaches the "theoretical intensity." The rather abrupt departure at $\frac{Kn}{M} \sim 1$ from the otherwise linear correlation has been shown by Fenn and Anderson (Fe 66) and Brown and Heald (Br 66) to be due to scattering of jet molecules which otherwise would contribute to beam intensity by background gas in the nozzle exhaust chamber.

This model can also be used to explain the results of figure 9 showing observed intensity versus nozzle-skimmer separation. For very small nozzle-skimmer separation the shock is swallowed into the nozzle and the beam passes through unimpeded. As the separation is increased slightly the shock structure abruptly appears in the free stream at the skimmer entrance thus reducing the beam intensity. The gradual attenuation of the effect of the shock with decreasing stream density as the nozzle-skimmer distance increases allows higher beam intensity until finally the effect of scattering of jet molecules by background gas at still larger distances is felt.
CHAPTER III

The Polarized Beam Apparatus

A. General

In 1963 Warren, Klinger and Axen (Wa 63) proposed a means of producing an intense beam of polarized He\textsuperscript{3} particles. A schematic presentation of the scheme along with their expected molecular flows at various locations is shown in figure 16. He\textsuperscript{3} gas cooled to 2.2° K passes through a supersonic Laval nozzle-skimmer collimator arrangement to produce an intense narrowly collimated beam. This beam enters a hexapole magnet in which the two nuclear spin states of the He\textsuperscript{3} are separated and one discarded. The particles are then ionized and accelerated thereby producing a polarized He\textsuperscript{3} beam.

B. The Low Temperature Beam Source

Figure 17 shows the design of the low temperature He\textsuperscript{3} atomic beam source. The He\textsuperscript{3} gas precooled to 77° K passes through a spiral heat exchanger before entering the liquid He\textsuperscript{4} bath at 4.2° K. The gas then passes through a helium bath maintained at 2.2° K before entering the Laval nozzle. Figure 18 shows in detail the nozzle-skimmer-collimator arrangement and table 1 summarizes the relevant dimensions necessary in calculating the expected beam flux.
Figure 16. Schematic Diagram Showing the Arrangement of the Components of the Polarized He$^3$ Ion Source. The Designed Beam Intensities are Given in Atoms/sec. and the Maximum Allowable Background Pressures in mm.Hg.
Figure 17. The Low Temperature He$^3$ Atomic Beam Source
Figure 18. Detail of Nozzle Assembly
### TABLE 1
Dimensions of Supersonic Beam System

<table>
<thead>
<tr>
<th>Diameter</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle throat</td>
<td>0.2 mms</td>
</tr>
<tr>
<td>Skimmer</td>
<td>0.4 mms</td>
</tr>
<tr>
<td>Collimator</td>
<td>0.1 cms</td>
</tr>
<tr>
<td>Magnet entrance</td>
<td>0.3 cms</td>
</tr>
<tr>
<td>Skimmer-Collimator distance</td>
<td>3 cms</td>
</tr>
<tr>
<td>Nozzle-skimmer distance</td>
<td>0.63 cms</td>
</tr>
<tr>
<td>Skimmer-magnet distance</td>
<td>15 cms</td>
</tr>
</tbody>
</table>

With a nozzle pressure of 15mm and assuming a Mach 4 beam Axen (Ax 65) calculated that 6.5x10^{15} particles per second would enter the magnet. Assuming a 40% transmission through the magnet and a 0.25% (Ve 64) ionization efficiency this would be sufficient to produce an ion beam of one microampere intensity.

Initial testing of the nozzle using He$^4$ gas carried out be Jassby (Ja 64) at room temperature and the nozzle-skimmer-collimator by Axen (Ax 66) at room and liquid nitrogen temperatures showed discrepancies in both beam intensities and Mach numbers from those expected from theoretical considerations assuming an idealized Laval nozzle system as proposed by Kantrowitz and Grey (Ka 51). In spite of these deficiencies it appeared that beam intensities adequate for the successful operation of the polarized He$^3$ beam source were available.
C. Testing of the Nozzle-Skimmer-Collimator System.

In order to carry out a more complete examination of the performance of the atomic beam source a series of measurements using He\(^4\) gas at room, liquid nitrogen and liquid helium temperatures was undertaken. Measurements were made with the magnet and ionizer chamber in place to examine at an early stage any alignment or vacuum problem that might arise so that modifications could be made to improve the overall performance of the system. Figure 17 and 19 show the relative location of the various components.

The pressure in the nozzle-skimmer region was measured with a Pirani gauge attached to a piece of tubing inserted just below the nozzle-skimmer axis as shown in figure 18. The pressures in the magnet entrance and ionizing regions were determined by use of ionization gauges. The beam intensity was measured with a differential Pirani detector (DPD) similar to one whose construction and calibration is described by Jassby (Ja 64). The DPD upon calibration was found to have a sensitivity of approximately \(4 \times 10^{12}\) molecules/cm\(^2\)/sec/\(\mu\)volt. The output from the DPD was measured using a Hewlett Packard Model 425 A DC Micro volt-ammeter capable of measuring \(1/10\) of a microvolt. The signal from the DPD was amplified by a Hewlett Packard micro volt-ammeter and used to drive a Moseley Model 680 chart recorder to provide an easily read record of the beam intensity. The beam was chopped after every reading to determine the reference background signal level. A block diagram of the recording system is shown in figure 20. A typical recording from the chart recorder is shown in figure 21. Figure 22 presents the results of beam operation at room, liquid nitrogen and liquid helium temperature plotted as a function of the pressure in the nozzle-skimmer region.
Figure 19. The Magnet Assembly
The nozzle-skimmer pressure measured in the location shown in figure 18 is used as an ordinate in plotting beam intensities as it is assumed that this pressure is simply related to the nozzle pressure. That this is in fact true, under certain conditions, is shown in figure 32. It is also assumed that the nozzle-skimmer pressure is an indication of free stream conditions just upstream of the skimmer. That this may in fact not be true is also shown in figure 32 where it shows that the relation between nozzle pressure and nozzle-skimmer pressure is roughly independent of nozzle-skimmer separation. One would expect the free stream pre-skimmer conditions to depend on the nozzle-skimmer separation and thus would expect a different relationship for each separation.
Figure 22. The Dependence of Beam Intensity on Temperature
D. Analysis of the Experimental Results

In order to assess the performance of our beam source it is useful to calculate the expected "theoretical beam intensity" using equation 9. If one uses the physical dimensions of the nozzle-skimmer system given in table 1, the Mach number as determined from figure 11, the physical constants given in table 2, and the fact that the DPD was 76 cm from the skimmer one obtains for selected nozzle-skimmer pressures the expected intensities tabulated in table 3.

**TABLE 2**

Selected Physical Parameters

For Helium\(^4\) Gas.

| \(Q_0\) | \(5.9 \times 10^3 \sqrt{\frac{T_{0K}}{P_{0K}}}\) cm/sec. |
| \(\gamma\) | 1.67 |
| \(N_1\) | \(9.66 \times 10^{18} \frac{P_{nm}}{T_{0K}}\) molecules/cm\(^3\) |
| \(\lambda\) | \(5.85 \times 10^{-5} \frac{T_{0K}}{P_{nm}}\) cms |
| \(M\) | 6.5 Nozzle-skimmer separation = 3.1 Nozzle diameters |

We have correlated in figure 23 the observed to theoretical beam intensities with the dimensionless parameter \(Kn/M\) (the ratio of Knudsen number to Mach number). Our Knudsen number is based on the skimmer diameter and the mean free path calculated using the temperature of the gas before it passes through the nozzle and the previously described nozzle-skimmer pressure. The Mach number is the free stream Mach number given by the Owen and Thornhill solution in figure 11.

Our correlation is similar to that of Fenn and Deckers (Fe 63) shown in figure 14 except that their Knudsen number is based on the free stream
### Table 3

**Selected Experimental and Corresponding Theoretical Beam Intensities**

<table>
<thead>
<tr>
<th>TEMP. ▯K</th>
<th>NOZZLE-SKIMMER PRESSURE</th>
<th>EXPERIMENTAL BEAM INTENSITY Atoms/cm²/sec.</th>
<th>THEORETICAL BEAM INTENSITY Atoms/cm²/sec.</th>
<th>$\frac{\lambda s/D}{M}$</th>
<th>$\frac{F_{2\text{exp.}}}{F_{2\text{theor.}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>25 microns</td>
<td>$0.72 \times 10^{14}$</td>
<td>$3.43 \times 10^{14}$</td>
<td>2.7</td>
<td>0.21</td>
</tr>
<tr>
<td>50</td>
<td></td>
<td>1.07</td>
<td>7.1</td>
<td>1.3</td>
<td>0.15</td>
</tr>
<tr>
<td>75</td>
<td></td>
<td>1.37</td>
<td>10.5</td>
<td>0.9</td>
<td>0.13</td>
</tr>
<tr>
<td>100</td>
<td></td>
<td>1.66</td>
<td>13.8</td>
<td>0.67</td>
<td>0.12</td>
</tr>
<tr>
<td>125</td>
<td></td>
<td>1.83</td>
<td>18.3</td>
<td>0.54</td>
<td>0.10</td>
</tr>
<tr>
<td>150</td>
<td></td>
<td>1.98</td>
<td>22</td>
<td>0.45</td>
<td>0.09</td>
</tr>
<tr>
<td>175</td>
<td></td>
<td>2.1</td>
<td>24.7</td>
<td>0.38</td>
<td>0.085</td>
</tr>
<tr>
<td>200</td>
<td></td>
<td>2.17</td>
<td>28.2</td>
<td>0.33</td>
<td>0.077</td>
</tr>
<tr>
<td>77</td>
<td>25</td>
<td>0.5</td>
<td>7.15</td>
<td>0.69</td>
<td>0.07</td>
</tr>
<tr>
<td>50</td>
<td></td>
<td>0.6</td>
<td>15</td>
<td>0.35</td>
<td>0.04</td>
</tr>
<tr>
<td>75</td>
<td></td>
<td>0.73</td>
<td>20.9</td>
<td>0.23</td>
<td>0.035</td>
</tr>
<tr>
<td>100</td>
<td></td>
<td>0.8</td>
<td>26.6</td>
<td>0.17</td>
<td>0.03</td>
</tr>
<tr>
<td>125</td>
<td></td>
<td>0.87</td>
<td>34.8</td>
<td>0.13</td>
<td>0.025</td>
</tr>
<tr>
<td>150</td>
<td></td>
<td>0.95</td>
<td>43.2</td>
<td>0.11</td>
<td>0.022</td>
</tr>
<tr>
<td>175</td>
<td></td>
<td>0.96</td>
<td>48</td>
<td>0.10</td>
<td>0.02</td>
</tr>
<tr>
<td>42</td>
<td>50</td>
<td>0.22</td>
<td>55</td>
<td>0.02</td>
<td>0.004</td>
</tr>
</tbody>
</table>
Figure 23. The Ratio of Experimental to Theoretical Beam Intensity as a Function of Knudsen Number to Mach Number.
pressure and temperature just upstream of the skimmer entrance rather than
the pressure and temperature we chose. It should be clear that the Knudsen
number used in figure 14 based on free stream conditions is not directly
comparable with the one used in figure 23.

From figure 22 we see that the beam intensities decrease with tempera­
ture for a constant nozzle-skimmer pressure rather than increase as expected
from the theory of Kantrowitz and Grey (Ka 51). It had been expected that
the beam at liquid helium temperatures would be about ten times more intense
than the room temperature beam; the sad fact was however that the beam was
about ten times less intense!

The correlation in figure 23 shows that we obtain only a fraction of
the full "theoretical beam intensity" for low Kn/M ratios but obtain an
increasing fraction of the theoretical for higher Kn/M ratios. This is
attributed to the fact that lowering of the gas temperature increases the
gas density thus lowering the mean free path and hence Knudsen number at
the skimmer entrance. This results in the gas being more severly "shocked"
at the lower temperatures than at the higher temperatures with a subsequent
attenuation in beam intensity.

The fact that the actual beam intensity at liquid helium temperature
is about 100 times less than expected led to a reassessment of the feasibility
of the polarized beam experiment. It was decided that an improvement in
beam intensity by a factor of 10 would be necessary to produce a polarized
beam of useful intensity. With this in mind a program was undertaken to re­
examine all aspects of our nozzle system and to consider alternate means of
improving the beam intensity. The results of these efforts will be des­
cribed in the next section.
CHAPTER IV

Investigations into factors affecting beam intensities

In reviewing the performance of our molecular beam system with a view to increasing the beam intensity we have examined many aspects of the beam formation. Some of the main points investigated include:

The effect of pressure and temperature
The effect of nozzle-skimmer distance
The effect of skimmer diameter and manufacture
The effect of a collimator
The effect of background pressure in the nozzle-skimmer region
The effect of various types of beam forming devices

Some of these points have been unsatisfactorily investigated or have given inconclusive results but in most cases have indicated in a general fashion the significance of the effect on beam intensity.

A. Nozzle-skimmer separation

In order to examine the effect of nozzle-skimmer distance on beam intensity it was first necessary to devise a means of easily adjusting the nozzle-skimmer distance. The scheme chosen is shown in figures 24 and 25. In this arrangement the skimmer-collimator distance is fixed to ease construction. The nozzle-skimmer distance is adjusted by revolving the skimmer-collimator carriage on a screw thread (26 threads per inch) cut on the main nozzle assembly. The gear on the end of the skimmer-collimator carriage is connected by means of a gear chain system to a rod which passes through the vacuum chamber wall using an O-ring seal thus allowing the rod to be rotated from outside the vacuum system. One complete revolution of
Figure 24. The Adjustable Nozzle-Skimmer Apparatus.
Figure 25. Turning Mechanism for Adjustable Nozzle-Skimmer Apparatus.
this rod corresponds to 1/8 of a revolution of the skimmer-collimator carriage which increases or decreases the nozzle-skimmer separation by .0048 inches. The skimmer is prevented from being forced against the nozzle by means of a collar which presets the "zero" revolution nozzle-skimmer distance at any desired value. The vacuum seal between the various differentially pumped regions is effected by means of two O-rings built into the skimmer-collimator carriage. Thus under room temperature operating conditions it was possible to fix the nozzle pressure then adjust the nozzle-skimmer distance by turning a handle on the outside of the vacuum system.

Some typical results obtained from the adjustable arrangement are shown in figure 26 for several nozzle pressures. Figure 27 shows the results one obtains by fixing the nozzle-skimmer distance then varying the nozzle input pressure. The results obtained are similar to those obtained by other experimenters and can be explained by the mechanism discussed previously. All results with the adjustable nozzle-skimmer arrangement have been made with a skimmer-detector distance of about 16 cm.

Obtaining similar results at liquid nitrogen temperatures is not as simple because the neoprene rubber O-rings freeze and it is impossible to rotate the skimmer-collimator carriage. We have considered teflon O-rings but as yet have not been able to obtain any for testing purposes. However, results can be obtained by fixing the nozzle-skimmer separation at room temperature then cooling the system to liquid nitrogen temperatures and then observing the beam intensity for varying values of input pressure. After obtaining one set of results it is then necessary to warm the entire system to room temperature, reset the nozzle-skimmer separation and repeat the procedure. If one selects several nozzle-skimmer separations it
Figure 26. Typical Results Obtained From Adjustable Nozzle-Skimmer Apparatus.
Figure 27. Typical Results Obtained for Fixed Nozzle-Skimmer Separation.
should be possible to get an idea of the dependence of beam intensity on nozzle-skimmer distance at liquid nitrogen temperatures. Just such a procedure was used in obtaining the results shown in figure 28. Room temperature results are included in figure 29 and 30 for comparison.

In order to compare these results with earlier results plotted on the basis of nozzle-skimmer pressure figures 31 and 32 have been compiled using the results associated with figures 28 and 30 for several selected nozzle-skimmer separations.

The results in figures 26 - 30 show clearly the effect of nozzle-skimmer separation on beam intensity and point out the advantages of optimum separation for a given nozzle pressure and total gas flow. The later item is extremely important as most beam sources have a limited pumping capacity. For example figure 26 shows for a fixed nozzle pressure that the beam intensity can be varied by a factor of 3 by nearly changing the nozzle-skimmer separation by 0.04 inches. Figures 28 and 30 illustrate how one can obtain a higher beam intensity, especially at lower temperatures, by keeping the nozzle-skimmer separation in the region before the minimum or valley shown in figure 29. Although such features as the exact location of the peak and valley shown in figure 26 and the value of the peak to valley ratio depend on the particular skimmer and possibly nozzle that one has in their system, this data should be extremely useful in serving as a guide in designing a system with maximum beam intensity and minimum total gas flow.

B. Mechanical alignment

Many of the difficulties involved with molecular beam systems are associated with the actual mechanical alignment of the nozzle-skimmer-collimator system. The physical alignment of these components of the
Figure 28. Beam Intensity Results at 77°K.
Figure 29. Beam Intensity Results at 300°K.
Figure 30. Beam Intensity Results at 300°K.
Figure 31. Correspondence Between Nozzle and Nozzle-Skimmer Pressures at 300°K.
Figure 32. Correspondence Between Nozzle and Nozzle-Skimmer Pressures at 77°K.
system is extremely important because of the relatively small diameters of the various apertures. Because of this it is necessary to follow an alignment procedure each time the beam assembly is dismantled. We shall discuss below the procedure used specifically in setting up the adjustable nozzle-skimmer apparatus but the procedure used is essentially the same as used with the fixed nozzle-skimmer apparatus.

The overall alignment set-up is shown schematically in figure 33. The framework which holds the nozzle and skimmer-collimator carriage is first inserted in the collet of the Colchester "student" lathe then inspected by means of an accurate dial indicator and adjusted until finally the inner surface on which the skimmer-collimator carriage runs is true to better than .001" when the collet is rotated. Following this the Wild Model T2 theodolite is focussed on the nozzle and the collet rotated. The nozzle is adjusted by means of four adjusting screws until there is no visible asymmetry upon rotating the collet. The skimmer-collimator carriage is then inserted into the main framework. Holding the main framework fixed, the carriage is rotated manually by means of the gear on the end. The skimmer is viewed through the theodolite and adjusted to minimize as much as possible, any visible asymmetry. The theodolite is then adjusted in the horizontal and vertical directions until its axis is coincident with the nozzle-skimmer axis. Finally the collimator is inserted and its position checked in the same manner as the skimmer.

If the alignment is not correct the beam intensity is no longer a smooth function of nozzle-skimmer separation as in figure 26 but now exhibits oscillations every 8 revolutions. Figure 34 is an example of very bad alignment. Some misalignment can also be detected in the 83mm Hg readings in figure 26.
Figure 34. Typical Results Showing Effect of Poor Alignment.

Figure 33. Alignment Assembly.
C. Effect of skimmer diameter and manufacture

The effect of skimmer diameter and manufacture on beam intensity has been investigated under rather limited conditions. We shall treat each separately in the following paragraphs.

1. Skimmer diameter

The original theoretical treatment of Kantrowitz and Grey predicts the beam intensity as a function of the diameters and separations of the skimmer and collimator, the pressure, the temperature, and the Mach number. As we have mentioned the theoretical and actual beam intensities appear to be related through the parameter $Kn/M$ where the Knudsen number, $Kn$, is a function of pressure, skimmer diameter and temperature. If one takes the case of constant temperature, Mach number, and pressure the observed intensity should increase roughly as the skimmer diameter. Thus if we double the skimmer diameter the beam intensity should also double. Naturally there is a limit to this line of reasoning but it was thought useful to increase the skimmer size and see if any increase in intensity resulted. No significant dependence of beam intensity on skimmer size was found. It is probable that the lack of control of skimmer quality obscured a possible dependence. It should be noted that Campargue (Ca 66) reports an increase in beam intensity of 30% upon increasing the diameter of his skimmer from 0.4 to 0.8 mm.

2. Skimmer Manufacture

Once one has determined the interior and exterior angles for the skimmer (see Axen (Ax 65)) it appears as if the only parameter, other things being equal, that could affect the extent to which the beam interacts with the skimmer is the sharpness and smoothness of finish of the skimmer edge. The manufacture of the skimmers and our observations as to the effect of
skimmer edges on beam intensity will be discussed below.

The general procedure for manufacturing the skimmer is as follows. The inside cone is machined out of the end of a piece of rod stock. A small hole, the diameter of the skimmer, is drilled into the stock using the inside cone as a centering device. This cone is then attached to a mating section thus allowing the material to be machined from the opposite direction. The outside cone is then machined off until the surfaces of the two cones meet. Figure 35 shows the general arrangement and what is meant by the "tunnel". The skimmers resulting from this procedure in general leave much to be desired as the thin edge tends to break up or a tunnel is left at the end.

Results from many skimmers of varying quality do not show any significant trends and it has not been possible to attribute some rather abrupt increases and decreases in beam intensity to the quality of the skimmer. It is possible, however, that the leading edge on the best of our skimmers is of such poor quality that a reduction in skimmer beam interaction and a resulting increase in beam intensity are still possible. Although not greatly affecting the beam intensity the amount of "tunnel" has been observed to change the character of the nozzle-skimmer separation versus intensity results.

D. Presence of Collimator

In order to reduce the number of factors upon which the beam intensity could depend we have removed, for many measurements, the collimator from our beam system on the assumption that it should not affect the beam intensity. It has however been our experience, at least with the adjustable nozzle-skimmer apparatus, that the beam intensities with the collimator
Figure 36. Pumping System for Nozzle-Skimmer Region.

Figure 35. Skimmer Manufacture.
removed are 2 to 3 times more intense than with the collimator in place.

This must mean one of two things; either the collimator is misaligned or the pressure in the skimmer-collimator region is too high. The fact that the skimmer-collimator separation is 3 cm and the collimator diameter is 1 mm makes it improbable that the small physical misalignments that could conceivably exist after our careful alignment could cause an attenuation of the size observed. It is, on the other hand, quite conceivable because of obstructions associated with the adjustable nozzle-skimmer arrangement that the pressure in the skimmer-collimator region is excessive. Unfortunately with our present experimental apparatus we are unable to measure this pressure.

We see no reason why our present pumping system should be incapable of handling the existing gas flow and thus feel that with suitable modifications we will be able to reduce the pressure in the skimmer-collimator region to an acceptable level. This means we will assume that beam intensities attainable without a collimator are for all intensive purposes attainable with a collimator.

E. Background gas Pressure

In an earlier section we presented an overall description of the expansion process from a nozzle into an evacuated region. This treatment suggests that the actual jet molecules upstream of the Mach disk remain unaware of the background gas in the nozzle-skimmer region because of the presence of a shock wave which acts as a barrier to outside influences. Downstream of the Mach disk the beam can easily be bombarded by the background molecules. With these thoughts in mind it was considered useful to determine experimentally the effect of the background gas in the nozzle-
skimmer region on the beam intensity.

The location of the Mach disk for many gases is given by equation 15. For helium, Abuaf (Ab 66) presents results (figure 13) which give for the same Knudsen number lower terminal Mach number than equation 15.

### TABLE 4

**Terminal Mach numbers**

<table>
<thead>
<tr>
<th>Nozzle Pressure</th>
<th>( \lambda ) mm</th>
<th>Kn</th>
<th>( M_T = 1.17x^{0.4} )</th>
<th>Nozzle diameters</th>
<th>Abuafs</th>
<th>Nozzle diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_o = 300^\circ K )</td>
<td>1.75x10^{-3}</td>
<td>8.7x10^{-3}</td>
<td>7.8</td>
<td>3.8</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>100 mm</td>
<td>4.4x10^{-3}</td>
<td>2.2x10^{-2}</td>
<td>5.4</td>
<td>2.4</td>
<td>3.5</td>
<td>1.5</td>
</tr>
<tr>
<td>40</td>
<td>1.75x10^{-2}</td>
<td>8.7x10^{-2}</td>
<td>3.1</td>
<td>1</td>
<td>No data</td>
<td>-</td>
</tr>
<tr>
<td>( T_o = 77^\circ K )</td>
<td>0.45x10^{-3}</td>
<td>2.25x10^{-3}</td>
<td>13.5</td>
<td>8.2</td>
<td>10</td>
<td>5.5</td>
</tr>
<tr>
<td>100 mm</td>
<td>1.13x10^{-3}</td>
<td>5.6x10^{-3}</td>
<td>9.3</td>
<td>5</td>
<td>7</td>
<td>3.5</td>
</tr>
<tr>
<td>40</td>
<td>0.45x10^{-2}</td>
<td>2.25x10^{-2}</td>
<td>5.3</td>
<td>2.2</td>
<td>3.5</td>
<td>1.5</td>
</tr>
<tr>
<td>( T_o = 4^\circ K )</td>
<td>0.023x10^{-3}</td>
<td>0.12x10^{-3}</td>
<td>43.7</td>
<td>&gt;&gt;30</td>
<td>28</td>
<td>&gt;&gt;25</td>
</tr>
<tr>
<td>100 mm</td>
<td>0.059x10^{-3}</td>
<td>0.29x10^{-3}</td>
<td>30</td>
<td>&gt;&gt;30</td>
<td>19</td>
<td>14</td>
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<td>40</td>
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<td>0.12x10^{-2}</td>
<td>17.4</td>
<td>12.5</td>
<td>13</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 4 gives the values of the terminal Mach number determined by both equation 15 and Abuaf's results for several selected nozzle pressures. Using the results of Ashkenas (figure 11) we have assigned a nozzle-skimmer separation corresponding to these terminal Mach numbers. From these results it is apparent that scattering by background molecules will be of importance at least at room temperature for almost all nozzle-skimmer separations and operating conditions that we wish to consider. Naturally the transition
between continuum and free molecular flow is not sharp and these results are only indicative of the approximate region where one might expect this mechanism to become of consequence.

Experimentally the dependence of beam intensity on background pressure in the nozzle-skimmer region was determined by constricting the pumping line to this region and thus increasing the background pressure. It was only possible to examine a limited range of background gas pressures because of the limited pumping capacity available and the conductance of the pumping line. Figure 36 shows the location of the pump, the valve, the pumping line and the nozzle-skimmer region.

Figures 37 - 41 show some typical results obtained by constricting the pumping line to the Leybold Hg 45 diffusion pump. Each figure presents results obtained using selected fixed nozzle pressures and a constant nozzle-skimmer separation. These results show how the expanding jet is protected from background gas scattering until the transition to free molecular flow occurs at the Mach disk. In figures 38, 39 and 40 an increase in background gas pressure reduces the beam intensity considerably whereas in figure 37 the beam intensity is slightly reduced for the 12 and 41 mm case and unaffected by the background gas intensity in the 100 mm case. As the results in table 4 show, however, the Mach disk should appear upstream of our nozzle-skimmer separations for all pressures if one uses Abuaf's results and for all except the 100 mm 4 nozzle-diameter case if one uses formula 15. The important thing to note here is the trend which shows clearly that for nozzle-skimmer separations considerably downstream of the Mach disk attenuation of beam intensity due to background gas scattering is considerable.

The increase in beam intensity at large background pressures is the
Figure 37. Beam Intensity Dependence on Background Gas Pressure.
Figure 38. Beam Intensity Dependence on Background Gas Pressure.
Figure 39. Beam Intensity Dependence on Background Gas Pressure.
Figure 40. Beam Intensity Dependence on Background Gas Pressure.
Figure 41. Beam Intensity Dependence on Background Gas Pressure.
result of the skimmer producing a simple oven beam. For large enough nozzle-skimmer (i.e. oven) pressures the beam intensity produced by this mechanism is quite large and appears, in some cases, to exceed that obtained with the nozzle beam but one must remember the extremely high gas pressures in the nozzle-skimmer region which are necessary to produce this sort of intensity. The oven beam could be useful if the total gas flow to the system was not excessive as it might eliminate the need for a recirculating He \(_3\) system.

F. Nozzles

The nozzle used in most of our experimental investigations has been described by Jassby (Ja 64). It was thought useful to consider two alternate beam producing devices. The first was a single channel capillary device, while the second was a multi-channel capillary device. The results obtained will be discussed below.

For devices of the single capillary type we used three different diameters. Two, 0.005" and 0.0095" inside diameter, were simply sections of stainless steel tubing while the third, 0.020" I.D, was a hole drilled in a piece of brass. The tubing was mounted by means of epoxy cement onto a holder which was then inserted in the same location as our usual nozzle.

The results obtained for the two diameters of tubing and one drilled hole are shown in figures 42, 43, and 44 for single fixed nozzle-skimmer separation. Because of the uncertainty in nozzle pressure, varying lengths, imprecise nozzle-skimmer separations and uncertain alignment no conclusions other than apparent beam intensity and general nature of the curves should be extracted from the results. Later results with the adjustable nozzle-
Figure 42. Performance of 0.005" Tubing Nozzle.

0.005" TUBING NOZZLE
NOZZLE-SKIMMER SEPARATION $\sim$ 3 TUBING DIAMETERS
TUBE LENGTH $\sim$ 20 TUBE DIAMETERS
ROOM TEMPERATURE
.018" SKIMMER + COLLIMATOR

BEAM INTENSITY (µVOLTS)

PRESSURE IN NOZZLE-SKIMMER REGION (MICRONS)
Figure 43. Performance of 0.0095" Tubing Nozzle.
0.020" HOLE
LENGTH OF HOLE ≈ 10 × DIAMETER
NOZZLE-SKIMMER DISTANCE ≈ 3 × DIAMETER
ROOM TEMPERATURE
0.018" SKIMMER + COLLIMATOR

Figure 44. Performance of 0.020" Nozzle.
skimmer assembly for a 0.0095" section of tubing at room and liquid nitrogen temperatures are shown in figures 45, 46, and 47. These results show that the tubing produces a beam with properties similar to those of our Laval nozzle.

The bundle of capillaries shown in figure 48 consisted of many individual tubings about 0.005 inches in diameter. For this set of measurements the skimmer and collimator openings were made by simply cutting round holes in thin metal sheets. The dimensions of the tested assembly are shown in figure 49. The results obtained are shown in figure 50. Although the intensities obtained are attractively large the large diameters of the skimmer and collimator allow an excessive flow of gas into the skimmer-collimator and magnet regions of our apparatus.

G. Summary

In our investigations into the properties of beam formation by miniature supersonic nozzle systems we have been guided by the desire to obtain highly intense yet narrowly collimated helium beams at low temperatures. The beam intensity from our nozzle system was found to decrease considerably upon cooling of the gas and beam assembly to low temperatures. The effect of nozzle-skimmer separations on beam intensity has been investigated in considerable detail and the advantages of optimum nozzle-skimmer separation are demonstrated. Background pressure in the nozzle-skimmer region has proven to have considerably affect on beam intensity providing the skimmer entrance is downstream of the "Mach disk". The beam intensity was found to be very dependent on actual physical alignment of the nozzle-skimmer-collimator system. Results obtained by varying the skimmer diameter were inconclusive. No positive results as to the effect of the sharpness of
Figure 45. Room Temperature Intensities for 0.0095" Tubing.
Figure 46. Room Temperature Intensities for 0.0095" Tubing.
Figure 47. Liquid Nitrogen Temperature Intensities for 0.0095" Tubing.
Figure 48. Bundle of Capillaries used as a nozzle.

Figure 49. Geometrical Arrangement of Multiple Capillary Device.
Figure 50. Performance of Multiple Capillary Device.
the skimmer edge were obtained although it is quite likely that the majority of our skimmers were so poor that any trends were obscured. Use of drilled holes and capillary tubing as nozzles showed that these devices produced beams of a similar nature and intensity to those produced by the Laval nozzle.
CHAPTER V

Beam intensities available for the polarized He\textsuperscript{3} beam source

In order to compare the results of beam intensity measurements made at various stages of development of the beam source it is necessary to relate the intensities to a common parameter. We have used the results in figure 31 to relate measurements made on the basis of nozzle-skimmer pressure to those based upon nozzle pressure. We have used the fact that beam intensity is inversely proportional to the square of the distance from the skimmer to relate intensities obtained with the differential pirani detector at different distances from the beam source. Using these conversion techniques we have plotted selected results on figure 51. The results indicated with the symbols \textcircled{X} and \textcircled{1} show the values of intensities obtained during the original testing of the nozzle source at room temperature. The results indicated by \textcircled{O}, \texttimes, and \textfilled{I} are representative of the intensities one can now reliably obtain at a nozzle-skimmer separation which keeps the total gas flow into the skimmer-collimator region reasonable. These results are typically 2 - 3 times greater than those originally obtained. The results indicated by \text trianglu are an example of results one can obtain with certain skimmer and nozzle arrangements. As can be seen from the figure these are approximately 10 times larger than those attainable for the same nozzle pressure with the original nozzle skimmer apparatus. Other results, not shown here, give beam intensities without a collimator approaching those corresponding to a DPD signal of 8000 $\mu$ volts for certain nozzle-skimmer configurations at room temperature and for nozzle pressures less than 100 mm Hg. Unfortunately we are unable, as yet, to reproduce
Figure 51. Comparison of Beam Intensities.
these intensities in a reliable fashion although there appears to be no reason why we should not eventually expect to achieve them.
CHAPTER VI

Possible Ion Currents from the Polarized He$^3$ Ion Source

From the results presented so far it is possible to estimate an approximate ion current from our Polarized He$^3$ ion source. If we assume that the beam intensities are of the same magnitude for He$^3$ and He$^4$ we can optimistically assume that we will have a beam corresponding approximately to a DPD signal of 5000 μ volts intensity at room temperature. From figure 22 we see that the beam intensity at liquid helium temperature ($\sim 4^\circ$K) is reduced from the room temperature intensity by a factor which is approximately proportional to the square root of the temperature ratio (i.e. $\sqrt{4/300}$). Thus, assuming the beam does not condense upon expansion, at $4^\circ$K we shall assume that the beam intensity is approximately 1/8 of the room temperature beam intensity. We shall take the differential Pirani detector calibration to be $4 \times 10^{12}$ molecules/cm$^2$/sec/μ volt and the area of the magnet opening to be $7 \times 10^{-2}$ cm$^2$. We will assume the beam intensity to be constant across the magnet opening. If we assume that 40% of the beam actually passes through the magnet (50% eliminated because of undesired spin and 10% losses) and that our ionizer, described by Vermette (Ve 64), has an efficiency of 1/4 of 1% we find a final ion current of approximately 0.02 μ amperes. This assumes that we are able to extract from the ionizer all those particles ionized, and focus them into a useful beam.
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