COUNT RATE AND THE HELIUM ATOM MICROSCOPE - REPORT ; 2

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Abstract

The purpose of this follow up report is threefold, to examine critically the requirements of our helium atom microscope as it is presently concieved, to predict it's likely performance and propose directions for the experimental programme. The structure of the report is as follows.

In Chapter I the need for an extremely intense incident helium beam of small cross sectional area is emphasized. Chapter II describes individually the factors which together conspire to make our proposed microscope extremely inefficient from the perspective of count rate, thereby justifying the call for an intense incident beam. Chapter III shows how without a beam of small cross sectional area, background gas pressures and background signal would both be unacceptably high. Contrast though "shadowing" effects is likely to be the major contrast mechanism for non cystalline targets and is described in chapter IV. The question of how intense an incident beam can be made is considered in chapter V. It is concluded that microscope operation with incident beam pressures in the molecular flow region is possible. That a small radius atom focussing mirror must be developed is concluded. Chapter VI presents an alternative means of obtaining improved count rate, namely through a planar array of zone plates. Although a microscope based on such a device would appear extremely difficult to realize, it is pointed out that the technological hurdles presently before us with respect to primary beam intensification are already considerable. Chapter VII finally concludes that efforts should be directed towards producing an intense focussed helium beam if the design, as it presently stand, has a realistic chance of success.

I. Introduction

Four weeks after the completion of report number one, the perspective has changed somewhat. One problem now stands out clearly as that upon which the feasibility of the entire project hinges, namely, the problem of low count rate. I will show that the resolution of this problem reduces to that of producing an extremely intense helium beam to illuminate the target surface, perhaps of intensity $10^3 \rightarrow 10^4$ times greater than is usual for experiments involving nozzle sources and of extremely small cross sectional area. Whether this goal is attainable on technical or theoretical grounds is not yet clear to me. I therefore present this follow up report as a basis for further discussions.

II. Primary Beam Intensity Requirments

I assume here we have decided upon a zone plate as the atom lens to image target surfaces for the reasons presented in my first report. The proposed scheme is shown schematically in Figure 1. Although this configuration satisfies the requirements of high spatial resolution, count rate is at a considerable premium for the following reasons:

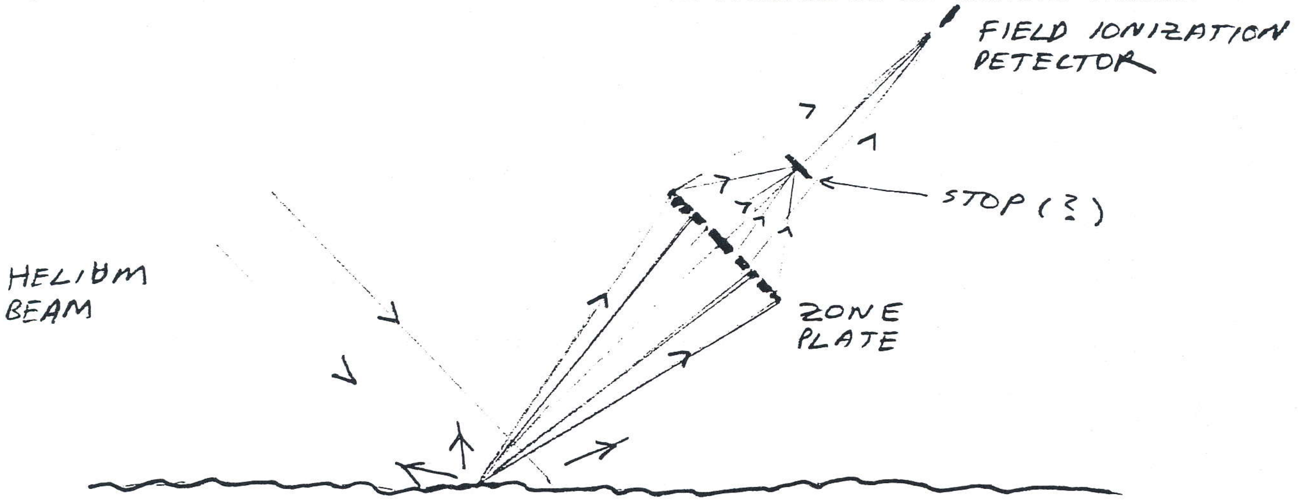

Figure II.1

Firstly, the zone plate subtends a tiny solid angle with respect to the target. Taking as an example the 200 μ, .4 μ resolution zone plate used by Carnal *et al* [1] with atoms of

$\simeq 2$ Å wavelength (20° K source), this solid angle turns out to be only 3.9×10^8 sr. One must furthermore reckon with a zone plate transmission of $\simeq 50\%$ and the fact that only 24 % of the transmitted intensity is directed into the $m = 1$ diffraction order. Finally, only the monochromatic elastically scattered electrons will be successfully focussed by the zone plate. The presence of inelastic collisions between incident helium atoms and the surface reduces signal levels and gives rise to background in the measured spectra. Although well ordered crystalline targets (largely uninteresting from the point of view of a microscope) can reflect atoms elastically with an efficiency greater than 50 %, perhaps as little as 10 % efficiency could be expected from an arbitrary non-crystalline target structure i.e. a biological specimen.

Taking all these factors into account and assuming both a detection efficiency of one for the field ionization detector [2] and isotropic scattering from the surface, the microscope would detect only one particle in $\simeq 10^9 \rightarrow 10^{10}$ scattered from an area of target surface, the size of which is determined by the instrumental resolution. Of course, the assumption of diffuse scattering is a worst possible case from the perspective of count rate, nevertheless, for an arbitrary non-crystalline target surface it represents a reasonable approximation in the absence of more detailed information.

Unfortunately, no high spatial resolution parallel detection system presently exists for the detection of helium atoms. This means that an image must be formed by sequential point by point measurements. In the optimum case, from the perspective of balancing the conflicting requirements of good count rate and resolution, the ionization area of the field ionization detector would be set to the diffraction limited resolution of the atom lens (zone plate) e.g. 4000 Å for the zone plate used in reference [1], the total resolution then being 1.41 times larger than this value. At any given time then, scattered atoms eminating from only a 4000 Å diameter area on the surface are being detected. For example, for the liquid nitrogen cooled helium source of reference [4] (7×10^{19} particles / sr / second) at a distance of .25 metres from the target surface, the number of scattered particles leaving such an area would be 2×10^8 per second. Multiplying this number with the attenuation factor of $\simeq 10^{-9} \rightarrow 10^{-10}$ derived above under the assumption of isotropic scattering and assuming the inelastic background can be neglected (see Section III), we come to a predicted count rate of $.015 \rightarrow .15$ c/s !! In other words, an enhancement in beam intensity by a factor of $10^3 \rightarrow 10^4$ would be required to reach a count rate of only 150 c/s !

I note also at this point that the assumption of an incident beam intensity of 7×10^{19} atoms/sr/sec may well be an overestimation for a low temperature atom source ($\simeq 20°K$), such is required to bring the zone plate focal length down to a reasonable size (.45 metres). Measurements [1] suggest a reduction in beam intensity by a factor of approximately 5 is anticipated in going from liquid nitrogen temperatures down to $20°K$ due to a broadening of the beam profile.

III. Primary Beam Spot Size Restrictions

Aside from the requirement of extreme intensity, the incident beam must be of extremely small cross sectional area, in order that only a small area of the target surface is illuminated. The reasons are as follows:

Firstly, as described in report 1, without an extremely small incident beam spot size the diffraction orders will overlap considerably in the image plane and $m \neq 1$ orders will contribute significantly to the measured spectrum. The introduction of a "stop" (see figure 1) between zone plate and image plane, proposed in reference [3] pg. 195, will in principle remove contributions from higher orders, however I have not yet discovered in literature whether this method has to date been applied successfully. In it's abscence, the smaller the spot size, the smaller is the contribution from $m \neq 1$ orders at the field ionization detector. An incident beam spot size of less than 30 μ may well be required to keep contributions from $m \neq 1$ orders to a low level.

From an entirely different perspective, without an incident beam of small cross sectional area, the background gas pressure could reach an unacceptably high level. For example, if one increases the intensity of a beam by a factor of 1000 without restricting it's cross sectional area, then clearly the background pressure will rise by a proportionate amount. A considerable collision rate between background gas atoms and the slow moving ($\simeq 20\ K$) atoms scattered from the target surface could then result over the macroscopically large distance ($\simeq .5$ metres) separating surface and zone plate e.g. for possible background pressures 10^{-3} to 10^{-4} torr. The results of detailed calculations concerning this problem will be presented at a later date.

Finally, in the same way that the background from $m \neq 1$ orders is dramatically reduced if the illuminated surface area is small, so is it also true for the inelastic contributions to the spectrum. This effect is illustrated in the diagram below.

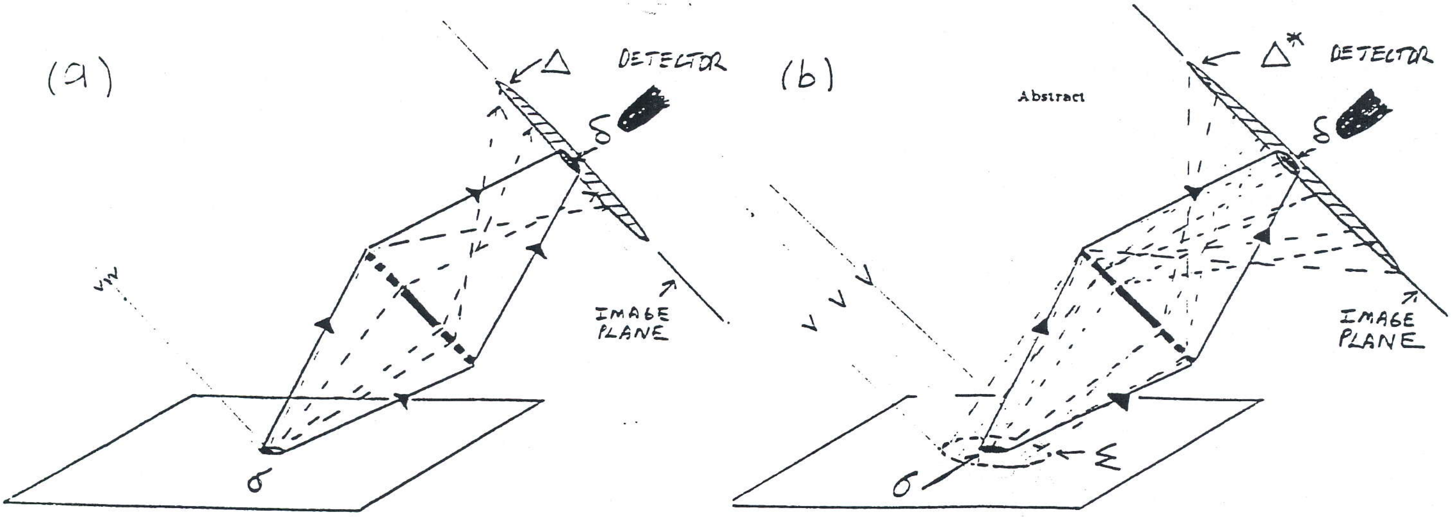

Figure III.1

In (a) the illuminated surface area is represented by σ. Elastically scattered atoms deriving from this area are focussed onto a small area δ at the image plane where they are recorded by a field ionization detector (I assume $\sigma \simeq \delta$ for simplicity). Inelastically scattered atoms, due to their finite momentum spread, are diffused over a much larger area Δ at the image plane. Thus inelastic background contributions are negligably small in this case. In (b) we enlarge the illuminated surface area to Σ whilst keeping the incoming beam intensity per unit target area unchanged. The situation is now entirely different. The inelastic scattered backround is now spread over an area Δ^*, only slightly larger than before, but the number of inelastically scattered electrons passing through the image plane per unit time has now been increased by a factor of $\simeq \Sigma/\sigma$. The signal strength from the area element σ at the image plane remains of course unchanged through this operation. Signal to background has thus been decreased by a factor $\simeq \Sigma/\sigma$!

In the limit of an extemely large illuminated surface area, the signal to background will approach the average ratio of elastic to inelastic scattering cross sections for the particular target under observation. Therefore, if the incident beam cannot be restricted to a small area, then we contend not only with the problem of how to subtract the background (which may not necessarily be flat), but also the fact that the concomitant reduced image definition (contrast) necessitates considerably longer data collection times to obtain an image of a prescribed quality. I note at this point that time of flight subtraction of the inelastic background would be impractical on the grounds of low duty cycle because count rate is at such a premium and indeed might not be possible on physical grounds, as reference [2] found the time response of the field ionization detector can be extremely slow.

As an illustration of the problems inelastic background introduces, reducing the elastic scattering probability from 100 to 10 percent for a given beam intensity would mean that from statistical arguments alone, the data collection time would have to be increased by 100 to maintain image quality due to the uncertainties introduced by the presence of background signal. We would then be talking about a required beam intensification of not $10^3 \rightarrow 10^4$ times but a $10^5 \rightarrow 10^6$!!!.

IV. Image Contrast for Diffuse Scattering Surfaces

This small discursion, although not completely unrelated to the general theme of this report, is included here to compensate for an omission in the first report, namely, the problem of contrast for non-crystalline targets.

It is all very well to talk of count rate a figure of merit for the microscope, however it is the contrast of the image formed that will largely determine the quality of information gleaned. If we wish to build a microscope capable of observing non crystalline targets, e.g. biological specimens, we must contend with the fact that every point over the target is essentially a diffuse scatterer. In this case, the main contrast mechanism will be through "shadowing", that is, through the fact that a direct line of sight between surface and zone plate does not exist at all positions on the surface. Contrast due to this effect should be extremely high although illumination of the shadowed regions through multiple scattering is still possible as indicated in the diagram below.

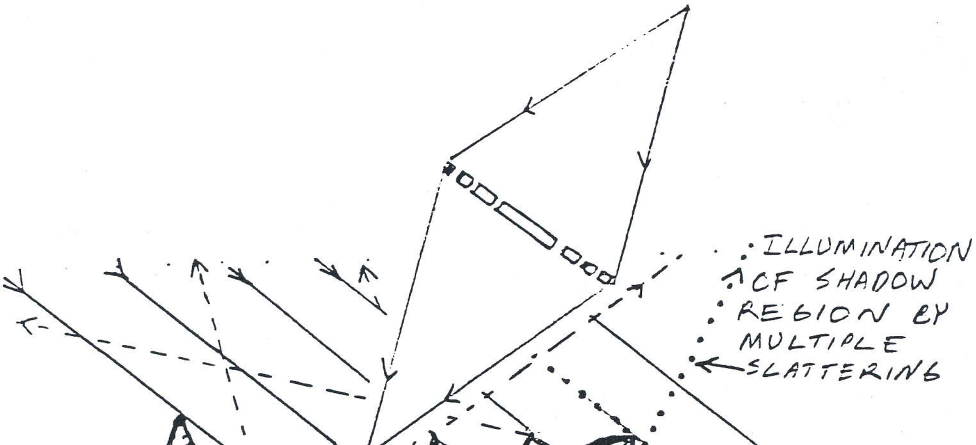

Figure IV.1

Of course, point to point variations in the elastic scattering cross section across the target surface, through variations in the phonon creation probabilities, will also result in image contrast, however these variations are likely to be small for biological samples i.e.

the exo-skeleton of an ant will not exhibit point to point variations in elastic scattering cross section as it is of essentially constant chemical composition over the entire body.

Here I have assumed that the structures are larger than the instrumental resolution and much larger than the incident wavelength in scale. The beam angle can of course be increased to enhance the effect, although this will result in an increased spot size on the surface, thereby reducing the beam intensity at the surface and adveresly affecting microscope performance for the reasons presented in section III.

V. Feasibility of Required Beam Enhancement

From the preceeding discussion it is evident that a highly intense incident atom flux is required to bring the data collection rate of the proposed atom microscope to an acceptable level. The fundamental questions to be answered are then the following : (*i*) At what point along the atom beam is the flow no longer describable as molecular ? (*ii*) If the flow is no longer molecular, does this necessarily degrade the microscope performance to an unacceptable level for a small illuminated target area ? It is these questions which I shall now address.

According to reference [4], the beam can first be descibed as molecular flow at the "sudden freeze" surface at a radius R_f from the nozzle given by the expression:

$$\frac{R_f}{D^*} \simeq (M_T)^{\frac{1}{\gamma-1}}$$

Assumed here is a terminal Mach number $M_T \gg 5$. γ is the ratio of specific heats (1.63 for He), A a calculated constant (3.26 for He) and D^* the nozzle diameter. For the 7×10^{19} atoms /sr/sec 10 μ source assumed in the example of section 2, R_f comes out to be 13 mm. Moving the source in that example from a distance of .25 meters to 13 mm from the target, the limit of molecular flow, would increase the beam intensity by a factor $(\frac{250}{13})^2 \simeq 370$ times. still short of our desired factor of 1000. According to the theory in which the above equation is derived. the radius of the sudden freeze surface can be reduced by reducing the nozzle dimension. however this then results in a considerable loss in beam intensity. Attempts to compensate for this through increases in source pressure may lead to clustering of the beam. Further problems arise when one tries to restrict the illuminated target area through the introduction of an aperture due to the effects of finite source size. the atom flux passing through the aperture being considerably diffused by the time it reaches the target surface. It certainly appears that a curved focussing mirror may be the only reasonable way for us to produce a localized beam of helium atoms of the required intensity. If it's radius of curvature were made very small. the adverse effects of surface mosaic spread. described in report 1. would be considerably reduced.

To the second question. whether the microscope could concievably be made to work with an incident beam pressure at the target surface exceeding the limit for molecular flow. the answer is in principle yes. Such a situation could concievably be reached with an atomic mirror. If the incident beam cross section could be made very small. then so would be the interaction region between the incident beam and scattered particles leaving the surface. In principle then. the probability of interaction between incident and scattered particles could be kept very low and the performance of the microscope not too badly affected (see figure below).

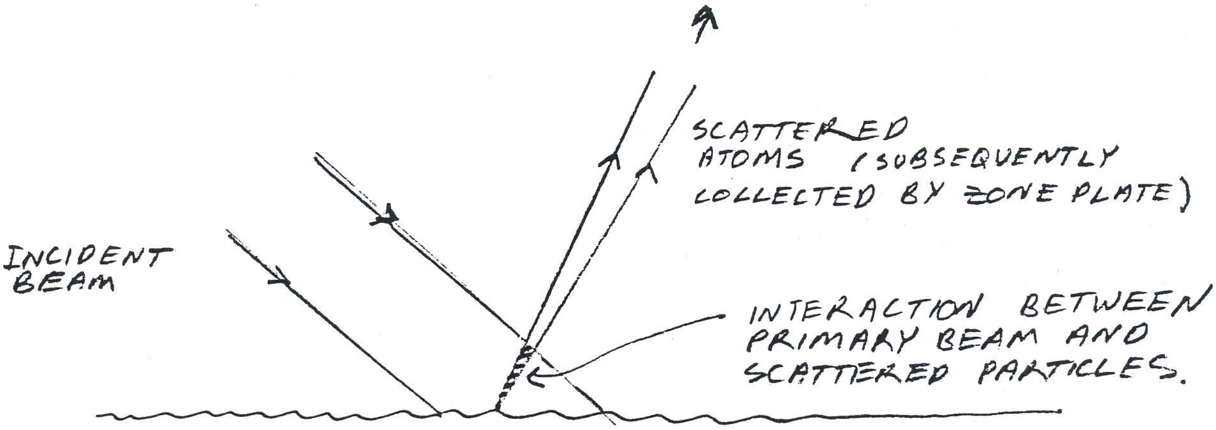

Figure V.1

Quantum mechanics says that there will always be a finite probability that a particle leaving the surface will not be scattered as it passes back through the primary beam (the interaction field falling off faster than $1/r^2$) in contrast to classical mechanics which says that all particles passing through a field will be scattered to some degree. even if it is by a minutely small amount. The degree of scattering. of course. will vary exponentially with the primary beam width and contribute to background in our measured spectra. Operation within "transition region" pressures may therefore be possible with concomitant increases in count rate if the scattering probability between incident and scattered atoms were not too high. I note however. that loss of beam monochromaticity could be a problem due to inelastic intra-beam collisions. A focussed beam has the advantage over a quasi-parallel intense beam that the constituent atoms are close together and hence in a high pressure enviroment only over the last stages of their trajectory. For a given beam intensity (atoms/sec/sr) the microscope count rate will be independent of the incident beam spot size at the surface. as long as it is larger than the instrumental resolution. There will. of course. exist a lower limit to the spot size to which a beam can be focussed for a given cross sectional area and velocity due to short range repulsive interactions between it's constituent particle.

In consideration of all of these factors. I will be performing calculations to establish limiting beam parameters in the near future.

VI. Parallel Detection for Helium Atoms ?

The best way to improve count rate would be to improve the efficiency of the detection system, that is clear. I therefore wish to finish with a crazy idea. Something like a planar array of 100 zone plate and 100 field ionization detectors could be imagined. Alignment would not necessarily be such a problem as each lens would not have to image exactly the same point on the surface. The target would then be scanned in a random fashion to build up an image, the field ionization detectors remaining fixed. I assume of course that differences in the positions of object points on the surface for each lens have first been measured (not necessarily so difficult). A computer would control the system and keep track of which counts were allocated to each position on the target as scanning proceeded. Mechanical stability of all components could well be a problem. A single channel plate detector in conjunction with a position sensitive anode could be used to detect the ionized helium atoms. This seems a rather complicated scheme, however I draw attention once again to the fact that the production of an incident beam of the required intensity and cross sectional area for our present design itself presents a considerable technological challenge.

VII. Conclusion

The feasibility of the Helium Atom Microscope, as the design is presently concieved, hinges upon the creation of an extremely intense helium beam to illuminate a small area of the target surface. Without this, the microscope will not function adequately. I earlier underestimated the difficulty in achieving this goal and did not fully appreciate all of the count rate degrading factors involved. The other two major components of the proposed microscope, the zone plate and the field ionization detector have, in contrast, been extensively investigated both theoretically and experimentally. It is now therefore my opinion that the construction of a test apparatus to investigate characteristics of both zone plate and field ionization detector, although of considerable importance, is secondary to the construction of an apparatus to develop and characterize intense helium beams. A sketch of a possible test configuration is shown in the figure below.

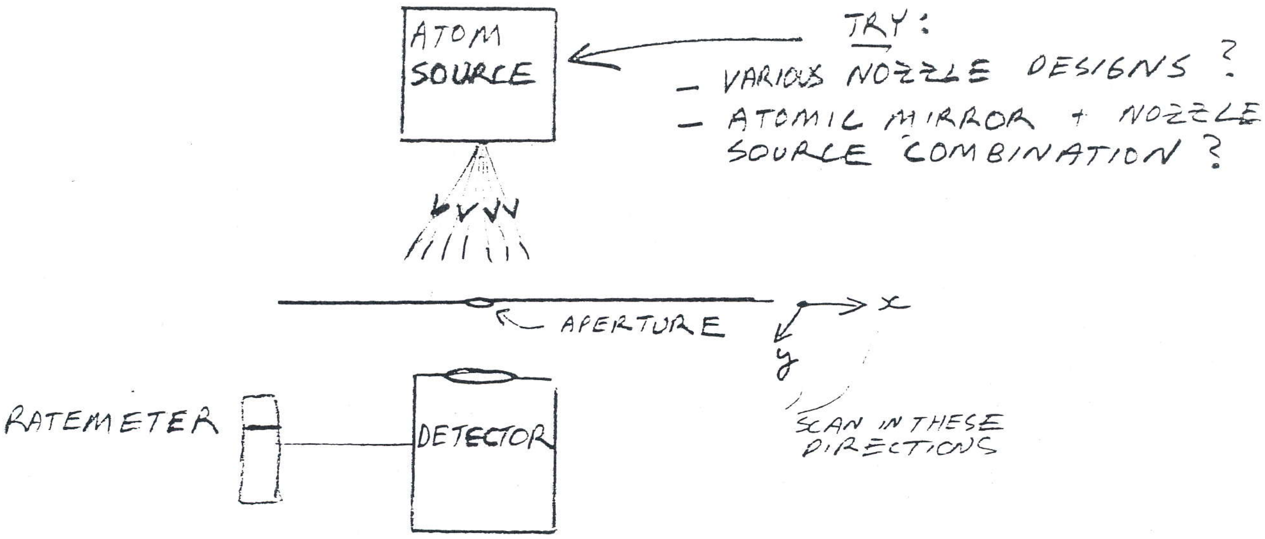

Figure VII.1

The only chance of reaching the required intensity and spot size presently appears to lie in the development of a high quality focussing atomic mirror. If it can be demonstrated that a beam of the required characteristics is attainable, then one could confidently set about designing and constructing the full microscope without the need of constructing a further test stage. If however, a sufficiently intense beam proved not attainable, then the design as it presently stands has little chance of success and the construction of further apparatus would seem unwarranted.

VIII. References

[1] O. Carnal, M. Sigel, T. Sleator, H. Takuma and J. Mylnek, "Imaging and Focussing of Atoms by a a Fresnel Zone Plate", submitted for publication (1991).

[2] J. W. McWane and D. E. Oates, "Field Ionizers as Molecular Beam Detectors", Rev. Sci. Instrum., Vol. 45, No. 9, (1974).

[3] G. Schmahl, D. Rudolph, P. Guttmann and O. Christ, "Zone plates for X-Ray Microscopy", Springer Series in Optical Sciences vol. **43**. Editors G. Schmahl and D. Rudolph (1984) 63.

[4] R. B. Doak, "Focussing of an Atomic Beam", submitted for publication (1990).