ENERGY-RELATED ATOMIC AND MOLECULAR
STRUCTURE AND SCATTERING STUDIES

MASTER

Annual Progress Report
for Period July 1, 1979 - June 30, 1980

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ABSTRACT

This report describes work performed during the past year on DOE Contract ER-78-S-02-4971. The basic goals of this program concern the experimental determination of properties of atoms and simple molecules that are important in a wide range of energy-related processes. In particular we have initiated measurements of polarizabilities of highly polar molecules and dimers, and of a number of atoms distributed through the periodic table, and, of the scattering of low energy electrons by highly polar molecules. For this latter series of measurements an entirely new apparatus has been designed and its external components have been completed. A new electron optics assembly has also been designed and is currently under construction. Details of all these projects are presented; analysis and data of the polarizability measurements are also given.

ANNUAL PROGRESS REPORT
July 1, 1979 - June 30, 1980

1. Introduction

On July 1, 1978 a new experimental program under DOE sponsorship was initiated in the Atomic Beams Laboratory at New York University. The basic goals of this program concern the experimental determination of properties of atoms and simple molecules that are important in a wide range of energy-related processes. In particular, we have undertaken two series of measurements on two separate beam systems. The first is a program to measure the polarizabilities of atoms, of some highly polar molecules and their dimers. The second is a program to measure cross sections for the scattering of electrons by highly polar molecules using the atomic beam recoil technique.¹ This latter program is to be undertaken on a new apparatus; its current status is described in Section 2 of this report. Other aspects of our program include measurements of hyperpolarizabilities, measurements of electron scattering cross sections such as by atomic O, N, C and U and excited-state cross section measurements. These, however, have not yet been started; they are described in the accompanying proposal for the period July 1 1980 - June 30 1981.

In Section 2 we describe progress on the new machine. In Section 3 we briefly discuss the atomic polarizability work. Section 4 gives details of our progress on molecular polarizabilities. Section 5 gives details of the electron gun design. Appendices 1 and 2 are copies of abstracts of talks to be presented at the Washington APS meeting, April 1980, on the dimer polarizability measurements, and at the Canadian Association of Physicists Annual Meeting, Windsor Ontario, June 1980, on scattering by highly polar molecules.

2. New Machine

The scattering program, with both the alkali halides and atomic elements such as N, O, C and U, requires an apparatus that will take advantage of essentially all aspects of modern beams technology. Our existing machines simply do not possess the required design features, including ultrahigh vacuum, high pumping speed, energy and angular resolution, stepping motor drives, and, most importantly, an interactive link with a data-processing computer. It was for this reason that three years ago we submitted a Capital Equipment grant proposal to the National Science Foundation, which was received

about two and one-half years ago, for \$47,900 for the construction of such an apparatus. About \$18,000 of the grant was used to purchase a PDP11/03 computer to control and process the data for the new machine. The remainder was used to purchase commercially available components (vacuum hardware, motions, drives, etc.), and for construction of chambers and other gear in the NYU Physics Department machine shop.

As described in our original proposal, the apparatus was to include a supersonic nozzle beam source to enhance intensity and sharpen the atomic beam velocity distribution for atoms and to also reduce the distribution of rotational states for molecules, a hexapole focussing and state-selection assembly - also for enhancing beam strength and in addition for producing ~100% polarized atomic beams in weak magnetic fields; mechanical velocity selection (required to transform accurately from recoil scattering angles to electron polar and azimuthal scattering angles)², a cylindrical electron monochromator, differentially scattered detection, with provisions for energy analysis, additional post-scattering atom beam velocity selection and an E-H gradient state analyzer³ after scattering. The atomic recoil analysis will be fully two-dimensional, in order to be able to unambiguously unscramble elastic, inelastic, and superelastic scattering events.⁴ To accomplish this it was necessary to devise a scheme that would enable the entire post-scattering part of the apparatus to rotate in two directions about the interaction center. This was accomplished by using two large bearing mounts and an elaborate counter-balance system.

Fig.2.1 shows a horizontal view of the apparatus, roughly to scale. It is about 5 meters long: it is vibrationally isolated from the laboratory floor using commercial (Barry Control) mounts. All the components are now in place, and the entire system is under vacuum as of this writing.

The source chamber has been designed so that it can be used with condensables or non-condensables, with supersonic nozzles or effusive sources. It is pumped by a 10" oil diffusion pump. A side chamber will allow us to install a cryogenic skimmer, for ease of operation with supersonic beams of condensable atoms. Hexapole electromagnets will be installed at both the entrance and exit ports of the buffer chamber, for state analysis and beam focussing. The same cavities housing the pole-pieces of the hexapole magnets can house electrostatic quadrupoles, to be used with molecular beams. The

buffer chamber will contain a rotating disk velocity selector, and rf cavities to help select a single hyperfine state. Side windows will also allow the use of laser beams to perform state selection by optical pumping.

The interaction chamber will allow the study of electron-atom or electron-molecule collisions with energy resolution of the order of 50 meV at 5 eV, for which a cylindrical electron monochromator (see Section 5) will be installed in a side chamber. Provisions have been made to allow for the illumination of the interaction region by a laser beam, either perpendicular to the plane defined by the atomic and electron beam, or parallel to the electron beam. The interaction region can be monitored for decay photons after impact excitation from three different angles in the plane defined by the electron and atom beams, or from a direction perpendicular to that plane. A movable electron detector can be installed to study the angular distribution of scattered electrons, in coincidence or independently of the recoil analysis of the scattered atoms. There is also room to install a Mott detector of the Rice University design for the polarization of the scattered electrons, and the electron spectrometer chamber can be extended to allow for the construction of a source of polarized electrons.

The detector chamber is mounted on the far end of a long (100 in.) I-beam, the upstream end being affixed to a system of two large diameter ball bearings, one vertical and the other horizontal, which are mounted on the interaction chamber, and centered at the scattering region. In this way we can ensure that the detector rotates around the scattering center. Between interaction and detector chambers there are an E-H gradient balance state analyzer and a long drift tube; the length of the drift tube helps provide both good angular and state resolution for the scattered atoms. The detector chamber allows the installation of surface ionization detectors for atomic systems that can be so detected, as well as atomic (or molecular) detection by impact or multiphoton ionization, or detection schemes involving a combination of excitation and/or ionization by both photons and electrons. The position of the detector (that is to say, the direction of motion of the recoiled atoms) is determined by stepping motor drive units, which in turn can be interfaced to the computer. Many other aspects of the experiments, from atomic and electron beam parameters to data collection and analysis, will also be handled by the computer.

The critical apparatus specifications are as follows: $\pm 1\%$ velocity resolution in the atomic beam; electron beam current of 10^{-7} A, with energy

Figure 2.1. A: Hexapole magnets. B: Two turntable ball bearings, centered at the scattering region, one in the vertical plane and the other in the horizontal plane. C: Counterweight system for the scanning arm. D: Computer-driven positioning devices for the detector chamber. E: Electron spectrometer chamber.

resolution of about 80 meV at 5 eV and 30 meV at 1 eV (in a recoil experiment it is necessary for both collision partners to possess comparable velocity resolution); angular resolving power, referred to the electron polar scattering angle, θ , will be better than 3° throughout, with somewhat higher resolution for small angle scattering (required for the study of highly polarized atoms or highly polar molecules); azimuthal electron angular resolution (for the study of spin-orbit and relativistic effects) will also average at 3° , except near $\theta=0$ and 180° . Our older apparatuses, with one dimensional analysis, used rectangular (ribbon) atom beams. The new apparatus, which analyzes in two dimensions, requires an atom beam of square cross section, and accordingly state selectors and beam focussers are of hexapole (atom) or quadrupole (molecule) design.

Using a post-scattering single rotating slotted disc, synchronized with the pre-scattering velocity selector, it will be possible to separate the "slow" from the "fast" component at a given recoil direction (a technique well-known in heavy particle scattering), thereby completely resolving scattering due to all elastic and inelastic channels in ground state scattering (see below for a discussion of excited state scattering). The assumption used in one-dimensional analysis (electron momentum $\ll$ atomic momentum) is not required in two-dimensional analysis, and accordingly it will be possible to extend our measurements to the important "intermediate" energy range, from 100 eV to several KeV. Figs. 2.2 - 2.6 show photographs of the new machine, taken in February, 1980.

One of our aims in designing the new apparatus was to ensure its maximum utilization, since it represents such a major investment in time and resources, in addition to its possessing such wide versatility. Accordingly we designed it so that limited time-sharing in several experiments would be possible. Thus, we are planning to run both atomic and molecular scattering experiments during the same period. The latter involves scattering of electrons by highly polar molecules (alkali halides). It is for this reason, for example, that the magnetic hexapole assemblies are interchangeable with electric quadrupolar ones. The DOE scattering program will therefore be time-shared with the NSF-sponsored research, which is primarily concerned with the study of state-to-state reactions involving electrons and excited states of simple atomic systems.

Fig. 2.2: New atomic beams apparatus. Detail: E-H gradient balance magnet housing, with alignment motions.

Fig.2.3: New atomic beams apparatus. Detail: mounting flange for electron monochromator, with x-y-z motion and electrical feedthroughs.

Fig. 2.4: Polarizability apparatus. From left to right: source chamber, velocity selector chamber, E-H gradient balance magnet, detector chamber.

Fig. 2.5: New atomic beams apparatus. From lower left to upper right: source chamber, velocity selector chamber, interaction chamber and detector motion bearings, drift tube.

Fig. 2.6: New atomic beams apparatus. From left to right: detector motion drives, detector chamber, drift tube, interaction chamber, velocity selector chamber and source chamber.

3. Atomic Polarizabilities

Once one gets away from a few particularly easy elements (e.g., alkali metals, barium, indium), both production and detection of most other elements of the periodic table becomes a non-trivial problem. In order to implement our goal of studying atomic polarizabilities we have therefore constructed a variable focus six-pole magnet.² A six-pole magnet serves to focus atomic beams by acting on the atomic magnetic moment (negative moment states). Such a focussing magnet can enhance beam intensities of the normal "inverse square" intensity, by from 50 - 100. Because we wish to study many different elements, with a wide range of magnetic moments and operating beam temperatures, our hexapole focussing magnet was designed with electromagnetic field coils, rather than the simpler, permanent magnets usually used.

Our focussing system had one additional requirement which makes it rather unique. We also wish to focus polar molecules, using the same beams apparatus for molecular polarizability studies. Generally speaking, because of the quadratic Stark energy of polar molecules, weak field focussing requires a four-pole electrode configuration, as opposed to the six-pole configuration for atoms (because of the linear Zeeman energy). Thus, it is not possible to use the same polefaces for both atoms and molecules, using insulated soft iron, as we do for our E-H balance magnets. Further, the magnetic yoke is very bulky, and it is therefore not desirable to have to remove it from the vacuum system when going from atoms to molecules. Accordingly we have built interchangeable 6- and 4-pole configurations, which can be fit inside the permanently seated magnet yoke. In switching from atoms to molecules, or vice versa, it will only be necessary to employ the appropriate set of pole faces. The machining of this system has been completed; the field coils are now in the process of being ground.

4. Molecular Polarizabilities

If we assume that our goal is to measure the dc electric dipole polarizabilities of alkali halide molecules and their dimers, we are immediately faced with the basic problem of how to separate true polarizability effects from those attributable to the permanent dipole moment of the monomer (the dimer does not possess a dipole moment). It is therefore essential to perform an analysis of the deflection characteristics of a beam of polar molecules under the action of a transverse, inhomogeneous electric field.

In this analysis we will assume that the beam contains a Boltzmann distribution of (J, m_J) states, where J, m_J are the rotational angular momentum and projection quantum number of J along the electric field E , assumed to be the quantization axis, respectively. We will assume that the distributions of (J, m_J) are uncorrelated with the beam speed, i.e., each constituent of the velocity distribution contains the full Boltzmann distribution of (J, m_J) .

For this analysis we also assume that "weak field" conditions prevail, that is, that the mean rotational kinetic energy $\gg$ potential energy of the rotating dipole in the applied electric field. This condition is readily satisfied under normal operating conditions, for typical applied voltages (~ 2000 V), assuming the electric dipole moment $\mu \approx 10$ Debyes, and $T \approx 10^3$ K,

$$\frac{\mu E}{kT} \approx 10^{-3}$$

For a small fraction of the beam, for which J is low, this condition is not satisfied, however, less than 1% of the full beam contains such low values of J , and we will therefore neglect these states in our analysis.

For weak fields the Stark Energy is

$$E_{\mu} = \frac{2A\mu_e^2 E^2}{h^2} \left\{ \frac{J(J+1) - 3m_J^2}{2J(J+1)(2J-1)(2J+3)} \right\}, \quad (4.1)$$

where A = molecular moment of inertia, perpendicular to the internuclear axis. We now calculate the deflection pattern, for a beam geometry as shown in Fig.1.

-Fig.1: geometric arrangement. Shaded beam is undeflected (δ -function) beam. Problem is to find $I(x')$.

Let I_0 = total beam intensity. We assume initially beam has infinitesimal width:

$$I_0(x) = I_0 \delta(x) \quad (4.2)$$

so $\int I_0(x) dx = I_0$ (4.3)

The initial beam possesses distribution functions over v, J, m_J :

$$I_0 = \int I_0(v, J, m_J) dv dJ dm_J, \quad (4.4)$$

We first obtain the deflection pattern for a given v, J, m_J . The deflection x' is easily shown to be:

$$x' = \frac{b^2 F_e(J, m_J)}{2m v^2}, \quad (4.5)$$

where $F_e(J, m_J)$ is the transverse force produced by the inhomogeneous electric field, b^2 is a geometry factor (dimensions ℓ^2), which depends on ℓ_1, ℓ_2, ℓ_3 ,

Now:

$$F_e(J, m_J) = \frac{\partial E}{\partial x} ; \frac{dE}{dx}, \quad (4.6)$$

where

$$\frac{dE}{dx} = \gamma E \quad , \quad (4.7)$$

with γ the "gradient constant" γ is determined from the geometry of the pole face configuration. It is usually in the range of 10 cm^{-1} . Using Eqs.4.1,7 we obtain

$$F_e(J, m_J) = \frac{\mu^2 \gamma A E^2}{2 \hbar^2 J^2} \left(1 - 3 \frac{m_J^2}{J^2} \right) \quad (4.8)$$

where we have neglected 1 compared to J . For x' we obtain

$$x' (v, J, m_J) = \frac{\beta}{v^2 J^2} \left(1 - 3 \frac{m_J^2}{J^2} \right) \quad (4.9)$$

where

$$\beta = \frac{b^2 \mu^2 \gamma A E^2}{4 m \hbar^2} \quad (4.10)$$

Dependence on m_J

If $E_\mu \ll kT$, we assume all m_J 's are equally populated, for a given J . Thus, the distribution function for m_J ,

$$df(m_J) = \frac{dm_J}{2J+1} \approx \frac{dm_J}{2J} \quad , \quad (4.11)$$

but since

$$m_J = J \cos \theta \quad ,$$

$$dm_J = J \sin \theta d\theta$$

and

$$df(\theta) = \sin \theta d\theta / 2 \quad , \quad (4.12)$$

where θ is the angle between $\vec{J}$ and $\vec{E}$. We now obtain the deflection intensity function $I(x')$ for a fixed v, J as a function of θ (or m_J).

$$I(x') dx' = I_o(v, J) \frac{\sin \theta d\theta}{2} \quad (4.13)$$

from Eq.4.9

$$dx' = \frac{6\beta \cos \theta \sin \theta d\theta}{v^2 J^2} \quad (4.14)$$

Combining Eqs.4.13,14

$$I(x') = \frac{I_o(v, J)}{4\sqrt{3}a} \cdot \frac{1}{\sqrt{1 - x'/a}} \quad (4.15)$$

where $a = \frac{\beta}{v^2 J^2}$: As a check, note that

$$I(x') dx' = I_0(v, J).$$

A plot of x'/a vs θ is shown in Fig.4.2

Fig.4.2: relative deflection x'/a vs θ . Negative x' corresponds to deflection in direction of convex poleface (strong field); positive x' to concave poleface (weak field).

On the figure ranges of θ corresponding to deflections toward the strong field (the convex poleface), $\theta < \theta < \cos^{-1} \sqrt{3}/3$ and toward weak field (the concave poleface), $\cos^{-1} \sqrt{3}/3 < \theta < \pi/2$ are indicated. In Fig.4.3 we plot $4\sqrt{3}aI(x')/I_0$ vs x' . Again, negative (positive) x' corresponds to strong (weak) field.

Fig.4.3: $4\sqrt{3}aI(x')/I_0(v, J)$ vs x'/a . Note the cutoffs at $x'/a = -2$ and $x'/a = +1$. Also note that $I(x')$ decreases monotonically with increasing negative x' (in the direction of strong field).

This figure shows that for a given v, J the beam is dispersed into the range $-2\frac{x}{a} < +1$, with the intensity increasing monotonically up to $x'/a=1$, where it cuts off.

Dependence on J

We now integrate the intensity, at a given v , over the J -distribution $f(J)$. We can obtain $f(J)$ as follows:

Write
$$f(J)dJ = f(E(J))dE(J) \quad , \quad (4.16)$$

with the normalized $f(E(J))$ given by the Boltzmann distribution

$$f(E)dE = \frac{2Je^{-\hbar^2 J^2/2 AkT} JdJ}{\int_0^\infty 2Je^{-\hbar^2 J^2/2 AkT} JdJ} \quad , \quad (4.17)$$

or

$$f(J) = \frac{4\sigma^{3/2}}{\sqrt{\pi}} J^2 e^{-\sigma J^2} dJ \quad , \quad (4.18)$$

where $\sigma = \hbar^2/2AkT$. Whence we can write

$$I(v, x') = \frac{\sigma^{3/2} v^2 I_0(v)}{\sqrt{3\pi} \beta} \int_0^{\sqrt{1-x'v^2 J^2/\beta}} J^4 e^{-\sigma J^2} dJ \quad (4.19)$$

The upper limit of integration depends on whether $x > 0$ or $x < 0$. Here we only concern ourselves with the $x < 0$ case. The reason for this has to do with the polarizability force. If α is the polarizability, then the force F_α is given by

$$F_\alpha = \frac{dE_\alpha}{dE} \cdot \frac{dE}{dx} \quad (4.20)$$

where E_α , the polarizability energy, is

$$E_\alpha = -\frac{1}{2} \vec{E} \cdot \alpha \vec{E} \quad (4.21)$$

with α the tensor polarizability. For simplicity we use α_{avg} , for which

$$E_\alpha = -\frac{1}{2} \alpha_{avg} E^2 \quad ,$$

and

$$F_\alpha = \alpha_{avg} E^2 / 2 \quad (4.22)$$

That is, the polarizability force is always to strong field, for positive α . Accordingly deflection patterns attributable to α_{avg} will be towards $-x$. To a fair degree of approximation α_{avg} , for either the monomer or the dimer, will not depend upon rotational constants, i.e., on J or m_J for the monomer or appropriate rotational quantum numbers for the dimer. Accordingly for the

polarizability force

$$I_{\alpha}(v, x) = I_0(v) \delta \left(x - \frac{b^2 a \alpha_{\text{avg}} E^2}{2mv} \right), \quad (4.23)$$

in other words, for a given v (and neglecting the anisotropy in α), the beam simply gets displaced, in the plane of the detector, by the amount $x' = b^2 a \alpha_{\text{avg}} E^2 / 2mv$. The actual intensity obtained will depend upon the velocity distribution, but in any case will always possess a peak in the direction of stronger field.

Because the deflection pattern in the strong field direction for the permanent dipole force is always monotonically decreasing as $(-x)$ increases, there can be no extremum in $I(x')$, even when integrated over I and v . Accordingly, should a peak be observed experimentally, it must be caused by polarizability forces (either the monomer or the dimer).

We now show some data obtained with a RbCl beam. Figs. 4.4-8 show plots of beam intensity vs displacement under various conditions of applied voltage and velocity selector parameters. Figs. 4.4, 5, 6 show the deflection pattern under applied voltages as indicated in the figures, without the velocity selector operating.

We now demonstrate that the polarizability peak is due to $(\text{RbCl})_2$, i.e., the dimer, rather than to RbCl. In Figs. 4.7, 8 we show the deflection patterns without and with applied fields, with the velocity selector set in its high resolution, high speed (i.e., RbCl) mode. Note that the polarizability peak is now missing. Accordingly it cannot be due to RbCl, and must therefore be caused by $(\text{RbCl})_2$. These data were obtained using our Nuclear Chicago multi-channel analyzer along with a stepping motor that automatically positions the detector at successive positions, so as to obtain reasonably long integration times. This is particularly important when the velocity selector is operating in the high resolution (narrow transmission) mode, and in fact we have thus far been unable to resolve the $(\text{RbCl})_2$ polarizability peak with the velocity selector set for $(\text{RbCl})_2$ transmission, because of the very weak beam obtainable in this mode.

In any case, we believe that we have succeeded in our first aim, to obtain polarizabilities of alkali halide dimers. Data have been obtained for KCl, RbCl, and CsCl; these are being presented in a contributed paper at the Washinton meeting of the American Physical Society (April 1980), copy attached (Appendix 1). We expect to complete the dimer measurements, and to obtain monomer polarizabilities during the coming renewal period.

In performing these experiments it is necessary to incorporate a velocity selector in order to distinguish monomer from dimer, etc. We have been fortunate in obtaining a convenient such device, on loan from ORNL. This is a six-disc slitted selector, which can be used in either a high resolution, low transmission or low resolution, high transmission mode. This selector was used in obtaining the data shown in Figs.4.7,8. Fig.4.9 shows the action of the velocity selector on an atomic potassium beam. Calculated and experimentally obtained curves are presented, normalized in intensity (but not in speed) at the peaks of the curves. It can be seen that agreement with a calculated Maxwellian distribution at the normal beam temperature is excellent (the depletion of low speed atoms is attributable to scattering of the beam by both background gas and by other beam particles).

FIG. 4.4: Beam deflection vs detector position,
 $+x \rightarrow$ (weak field) to left of origin.
 Curve A: No applied voltage (undeflected
 beam), B: $V = 1015$ V, C: $V = 1560$ V.
 Note two peaks beginning to appear in C.

V	d	α
1.01	- 3.05	84.7
1.56	- 6.1	71.0

Fig.4.4 $+x \rightarrow$

$-x \rightarrow$

FIG. 4.5 Beam deflection vs detector position, as in Fig. 4.4. Curve D. $V = 2080V$
 The "polarizability" peak, on right side, and permanent dipole moment peak
 on left side, are now well-separated. Assuming polarizability peak is
 close to $(RbCl)_2$, ratio of $(RbCl)_2/RLCl \approx .08$.

FIG. 4.6 Beam deflection vs detector position
as in Fig.4.4. Curve E, $V = 4040$ V.
Curve F, $V = 4610$ V.

4.04 25.01 43.4

4.61 29.9 39.9

FIG. 4.7: Beam deflector vs detector position with velocity selector in high resolution mode set to transmit RbCl at its most probable velocity. Curve A, no field. Curve B, $V = 1185$ V.

FIG. 4.8: Beam deflection as in Fig. 4.7.

Curve , $V = 1595 \text{ V}$

Curve , $V = 2210 \text{ V}$

5. The Electron Gun

5.1 Basic Design Considerations

The electron gun was of course designed with the particular requirements of the recoil experiment in mind. The electron beam was to be ribbon shaped, long in the direction of the atomic beam (~ 1 in.), and narrower than the atomic beam ($\leq .020''$), as shown in Fig. 5.1. The desired energy range was $0.5 \text{ eV} \leq E \leq 20 \text{ eV}$, with an electron energy resolution of 50 meV at 5 eV energy. The angular divergence at the interaction region was to be as small as possible ($\leq 3^\circ$), and finally, a useful electron current of 10^{-7} amps was desired. Clearly a cylindrical monochromator is needed. Such a monochromator was first described by Hughes and Rojansky.⁵ It consists of two coaxial cylinders with an inverse first power field between them. Electrons of the correct energy are refocussed after $127^\circ 17'$, and electrons of incorrect energy are deviated elsewhere.

The maximum current transmission of a cylindrical monochromator of mean radius r_0 is achieved if the entrance and exit slits (or their images) are the same size w , and the launching angle into the monochromator is given by $\alpha = \sqrt{3w/4r_0}$.⁶ Then, the energy resolution is $\Delta E_{1/2}/E = (5/3)\alpha^2$. In analogy to Kuyatt and Simpson's⁷ work on cylindrically symmetric electron beams, the maximum current is achieved by launching the space charge limited current into the monochromator as shown in Fig. 5.2. From Klemperer,⁸ the space charge limited current is $I/V^{3/2} = \alpha k \ell / Z_F$, where $k = 1.04 \times 10^{-6} \text{ Amp/V}^{3/2}$, ℓ is the length of the spatter slit, $\alpha = 4/Z_F$, and $\phi = 2w$. Combining this with the equation for α above gives $I/V^{3/2} = 3k\ell/8r_0$. The monochromatized electron current $I_{\text{mon}} = (\Delta E_{1/2}/\Delta E_K)I$.

Incorporating the monochromator into the selecting system, the general elements of the electron gun are shown in Fig. 5.3. Before the monochromator the lenses transport the beam from the cathode while launching the beam into the monochromator in the proper way. Everywhere but at the monochromator entrance, we want space charge effects to be negligible, thus, we use a fixed ratio decelerator right before the monochromator, as shown in Fig. 5.4.

In order to form a parallel beam of known current density, for the cathode we will use a space charge limited diode of the Pierce type (see Fig. 5.4). For such a cathode the current density is $J = 2.33 \times 10^{-6} V_A^{3/2} / d^2$. To achieve the space charge limited current at the monochromator entrance, we must be able to

compensate for current losses in the gun by changing V_A . Therefore the anode is made part of the first element in a three-element zoom lens.

In general, two apertures are necessary to collimate the beam. The window defines the size of the beam r_w , and the pupil defines the angle of the rays which make up the beam, $\theta_p = r_p/2$ (see Fig.5.5). Also defined is the beam angle $\theta_b = r_w/2$. It is advantageous to minimize the divergence $\theta_b + \theta_p$, but θ_p is limited by the Helmholtz — Lagrange law. However, the beam angle can be made arbitrarily small if the effective pupil is neutral and at infinity. This can be done by placing the pupil at the focus of the lens.

The collimating apertures were placed after the zoom lens (see Fig.5.4). Then an einzel lens was used to transport the beam, as well as to image the pupil at the focus of the declination, thus giving zero beam angle at the monochromator entrance.

The monochromator is operated at one particular energy, so after the monochromator one needs an energy changing lens which will allow one to vary the final energy from 0.5 - 20 eV. A lens which accomplishes this is the five-element afocal lens.⁹ Its advantage over an ordinary zoom lens is that if two objects are an axial distance ℓ apart, they will be imaged the same distance ℓ apart. Thus if the pupil is at infinity before the afocal lens, it will be imaged at infinity, giving a beam angle of zero and hence, a minimum divergence. This is accomplished, as well as zero beam angle at the monochromator exit, by placing the two collimating apertures between two triple-element lenses and at their foci (see Fig.5.4).

5.2 Expected Beam Properties

Optimizing the interconnected system of electron source, monochromator, lenses and collimators give the electron gun as shown in Fig.5.6. For this system $\alpha = .024$, $r_0 = .900''$, and the operation energy of the monochromator is 7 eV. For the oxide coated cathode that we will use $\Delta E_K = .170$ eV, and hence, the monochromator current $I_{mon} = 3.1 \times 10^{-6}$ Amp. Because of aberration losses of 10% in the lens system after the monochromator $I_{mon} = 2.8 \times 10^{-6}$ Amp.

The calculated energy spread at the monochromator is 7 meV, but this is certainly too optimistic for the energy spread at the target. Aberration, space charge spreading, and the Boersch effect all tend to increase the energy spread. However, our goal of 50 meV at 5eV appears to be readily achievable.

The afocal lens used can provide electrons in the energy range 0.44 eV - 112 eV. In the absence of a slit before the target, and ignoring aberration

effects (always $\leq 13\%$) the divergence of the beam varies from 2.8° at 44 eV to 1.1° at 20 eV, and 0.8° at 112 eV. The beam width is always less than .010". Putting a slit before the target has the advantage at low energies where space charge effects will be important in cutting down on the current density, and at higher energies of placing a maximum angle of acceptance on the part of the beam which is aberrated. For a slit of .012" at the position (57) shown in Fig. 5.6 for 0.44 eV a divergence angle of 0.6° and a current of 3.5×10^{-7} is calculated, for 3.6 eV a divergence angle of 1.6° and a current of 2.8×10^{-6} Amp, and for 112 eV a maximum angle of acceptance for the aberrated beam of 2.7° and a current of 2.8×10^{-6} Amp.

5.3 Construction of the Electron Gun

In designing the gun elements, the lens properties such as lens geometries, focal lengths, and aberration coefficients were taken from the tables of Harting and Read.¹⁰ Rectangular tube lenses were used with inner dimensions of 2.0" x (.100" - .250"), and outer dimensions of 2" x 1.1". The lens elements are being made from OFHC copper. The slits are being machined from .004" thick molybdenum. All the slits are 1" long to give the desired beam geometry.

The cathode end plate (A in Fig. 5.6), aside from being a clamping plate, also harbors the cathode, and has its electrodes shaped in the Pierce configuration. The cathode is held into place by a .010" tantalum holder which screws onto the cathode end plate top and bottom. The cathode is an oxide-coated nickel cathode from a Sylvania 6KG6 tube.¹¹ The heaters fit inside its .055" x .238" x 2.1" volume. Except for the front surface, the coating will be scraped off, leaving an emitting surface of .055" x 1.73". All support plates and mounting rods will be machined from non-magnetic stainless steel. The element B closest to the cathode is being machined from molybdenum to avoid poisoning the cathode.

For electrical insulation between the various electrodes we use 1.5 mm ruby balls. These ruby balls also play an important part in the alignment of the various components. On each surface there are three holes, and ruby balls sit in these. The slits are fixed into position by dowel pins. As can be seen in Fig. 5.6, the ruby ball insulators are hidden from the view of the electrons, to prevent these from charging up.

The selector assembly will be assembled first. It consists of the OFHC copper concentric cylinders sections, sandwiched between two grounded support plates. The concentricity of the cylinders, as well as the electrical

insulation is achieved by using the ruby balls. Mounted on the support plates are a top and bottom intermediate electrode to prevent fringing fields. These are insulated using remcolex shoulder washers of .010" mica. Three $\frac{1}{4}$ " stainless steel rods fastened to the support plates pass through oversized holes in the cylinders and clamp this assembly together.

Then starting from the selector assembly each arm of the gun is built up, stacking electrode elements onto ruby balls. Finally, the corresponding endplate is added. Three $\frac{1}{4}$ " stainless steel rods, fastened at one end to the selector and at the other to the endplate, clamp the gun arm together. At the endplates, the insulators used will be aluminum oxide washers.

The entire assembly is then mounted onto a top and bottom support plate fastened to the endplates and to the selector assembly. This in turn is mounted onto a rod which is attached to a motion, which gives movement in three perpendicular directions.

Elimination of stray magnetic fields which might disturb the prescribed electron path will be achieved by surrounding the whole electron monochromator in mumetal shielding. If this is not enough to achieve the necessary shielding (~1 mg) then a pair of Helmholtz coil wires will be installed.

Fig. 5.1: Interaction region geometry

Fig. 5.2: Input to monochromator

Fig. 5.3: Schematic of electron gun

Fig. 5.4: Optical elements of electron gun

Fig. 5.5: Detail (see text, p. 24).

Fig. 5.6

A..	Cathode endplate, Tantalum holder, Cathode
B.	Spacer which holds slit anode in place
S ₁	Slit anode .008" x 1"
CDE	Anode zoom lens (voltages on CD adjusted to give space charge limited current at monochromator entrance).
D	Deflector lens
S ₂ , S ₃	Collimating slits .004" x 1"
Pl	Slit holding plate
F	Deflector lens
GHI	Einzel lens
IH	Deflector lens
IJ	Decelerator lens
S ₄	Spatter slit (for proper launching into monochromator [2y in previous discussion] .007" x 1").
K	Maintains field free region Selector assembly, as described
LMN	Fixed ratio lens
M	Deflector lens
S ₅ , S ₆	Collimating slits .014" x 1"
O, Q	Maintains field free region
P	Deflector lens
RST	Fixed ratio lens
TUVWX	Five-element afocal lens (voltages on UWX adjusted to give different final energies)
X	Target endplate.
S ₇	Target slit .012" x 1"

Fig. 5.6: Machine shop drawing of monochromator
 Scale: 1.5X

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11. These have been supplied to us in unactivated batches by the Sylvania Corporation, to which we extend our grateful appreciation.

Appendix 1

Abstract Submitted
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Molecular Structure

Measurements of Electric Dipole Polarizabilities of Alkali Halide Dimers. * R. KREMENS and B. BEDERSON, New York University, and J. STOCKDALE, Oak Ridge National Laboratory. --We have initiated a program to study electric polarizabilities of highly polar molecules. In this preliminary report we describe measurements of space-average dc polarizabilities, $\bar{\alpha}$, of several alkali halide dimers. These systems lack permanent dipole moments, and hence the deflection pattern of a dimer molecular beam in an inhomogeneous electric field can be analyzed in terms of the polarizability alone. An alkali halide oven is heated to obtain optimum dimer concentrations (usually 4-8%). The resulting deflection pattern consists of a superposition of a monomeric beam profile, and one due to the induced dipole (polarizability) force on the dimer. The absolute polarizabilities can then be determined by normalization, i.e., by comparing the dimer deflection profile to those of known systems, such as the alkali atoms. Preliminary values are $\bar{\alpha} (\text{CsCl})_2 = 29.2$ and $\bar{\alpha} (\text{KCl})_2 = 48.4 (\pm 20\%)$, in units of $\text{\AA}^3$.

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No preference for
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Appendix 2: "Electron Scattering by Highly Polar Systems", Abstract of invited talk to be presented at the Annual meeting of the Canadian Association of Physicists, Windsor, Ontario, June 1980.

The scattering of atoms and simple molecules that possess unusually high electric dipole polarizabilities (e.g., alkali atoms and dimers, alkali halide molecules and dimers) by slow electrons presents unique challenges in both theory and experiment. Recent work involving elastic and inelastic scattering of ground and excited states by such systems will be reviewed. The special difficulties resulting primarily from the long-range nature of the r^{-4} potential, and the subsequent demanding requirement of high angular resolution in the forward scattering direction, will be noted. Effects caused by the usually high anisotropy of highly polarizable systems, and the problems associated with effecting proper comparison of theory and experiment will also be discussed.

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