ATOMIC AND MOLECULAR PHYSICAL AND OPTICAL OBSERVATIONAL SPECTROSCOPY AND BREAKDOWN

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13. ABSTRACT

Task I: "An electron time-of-flight spectrometer, designed for high-resolution electron spectroscopy in the 1 to 1/00 eV range, has been built and tested."

Task II: "A new apparatus has been designed and constructed for studying the dissociative excitation of H_2 by electron impact. When the apparatus becomes fully operational, an improved measurement of the velocity distributions of the metastable H(2s) atoms, resulting from the dissociation of the hydrogen molecule, will be made."

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Final Technical Report for Period Ending

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"Electron Time-of-Flight Spectroscopy in the 1 to 1/100 eV Energy Range"

Task I

1. Introduction

This final report describes the state of research at the time of termination of support. The research program is not yet completed.

During the three years of ARPA support we were able to start a major new experiment, to build the system and to perform preliminary tests. If the National Science Foundation responds favorably to a proposal submitted, the work will be continued.

In order to make this report as complete as possible at this time, the scientific problems of interest are again described in Section 2, followed by a description of the experiment in Section 3. The experimental apparatus developed during the time of the research contract is described in Section 4.

2. Scientific Interest

The study of electron interactions with atoms and molecules yields cross sections for elastic scattering and for the various inelastic processes: excitation, ionization etc. The variation of these cross sections as functions of the electron energy contains information on the structure of the atoms and molecules. Good experimental data on cross sections can be used for improving our theoretical understanding of atoms and molecules. The data are also useful for untangling and understanding the processes in complicated systems like weakly ionized plasmas, which are of importance in astrophysics, ionospheric physics and gas-laser technology.

Resonances are rapid variations of the cross section in a small interval of the electron energy. They occur when the electron forms a temporary compound state with the atom or molecule. Resonances were first discovered in nuclear physics where cross section measurements with high energy resolution are used as a very valuable diagnostic tool for unraveling the structure of nuclei. In atomic physics, similar resonances were discovered only after techniques for producing monoenergetic electron beams had been developed.[1,2]

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1. G.J. Schulz, "Resonances in Electron-Atom Collisions", in Atomic Physics, V.W. Hughes, B. Bederson, V.W. Cohen and F.M.J. Pichanick eds., Plenum Press, New York 1969, p. 321.

2. H.S. Taylor, G.V. Nazaroff and A. Golebiewski, "Qualitative Aspects of Resonances in Electron-Atom and Electron-Molecule Scattering, Excitation, and Reactions", J. Chem. Phys. 8, 2872 (1966).

In electron scattering from atoms, the resonances which have been observed occur at energies on the order of 10 to 20 eV and correspond to excited states of the negative-ion compound.[3] Resonances at lower energies, corresponding to the ground-state configuration, have been expected but have not been found.[4] In electron scattering from molecules, however, resonances corresponding to the electronic ground state of the negative ion have been observed. A notable example is the resonance in molecular nitrogen at about 2.3 eV, which is the vehicle for effective vibrational excitation of N_2 by electron impact.[5] This excitation mechanism, followed by excitation transfer, facilitates laser action in the N_2-CO_2 laser.[1]

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3. G.J. Schulz, "Experiments on Resonances in the Elastic Cross Section of Electrons on Rare-Gas Atoms, Phys. Rev. 136, A650 (1964);
C.E. Kuyatt, J.A. Simpson and S.R. Mielczarek, "Elastic Resonances in Electron Scattering from He, Ne, Ar, Xe and Hg", Phys. Rev. 138, A385 (1965);
G.J. Schulz, "Experiment on the Resonance in the Elastic Scattering of Electrons by Atomic Hydrogen", Phys. Rev. Letters 13, 583 (1964);
J.A. Simpson and U. Fano, "Classification of Resonances in the Elastic Scattering Cross Section of Ne and He", Phys. Rev. Letters 11, 158 (1963);
U. Fano and J.W. Cooper, "Identification of Energy Levels of Negative Ions", Phys. Rev. 138, A400 (1965).

4. D.E. Golden and H. Nakano, "Absence of Quasibound Negative-Ion Ground States of He and H_2 in Electron Scattering", Phys. Rev. 144, 71 (1966) and references given there.

5. G.J. Schulz, "Vibrational Excitation of Nitrogen by Electron Impact", Phys. Rev. 125, 229 (1962);
G.J. Schulz and H.C. Koons, "Energy Levels of the Compound State of N_2 Near 2.3 eV", J. Chem. Phys. 44, 1297 (1966).

Resonances in electron-atom scattering were made observable by the development of electron monochromators which reduce the energy spread in the beam from the cathode spread of 0.5 to 0.2 eV to values of 0.05 to 0.02 eV.[6] (The state of the art today is characterized by spreads as small as 0.01 or even 0.005 in a few cases,[7] but most cross section measurements have been made with energy resolutions not quite as good.) Further improvements of the experimental technique would be very worthwhile. It is possible that more resonances exist than have been observed. If the compound state has a lifetime of 10^{-13} sec or longer, the corresponding resonance is too narrow to be observed with present techniques.[1,8] At electron energies in the milli-volt

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6. P. Marmet and L. Kerwin, "An Improved Electrostatic Electron Selector", Can. J. Phys. 38, 787 (1960);
A. Stamatovic and G.J. Schulz, "Characteristics of the Trochoidal Electron Monochromator", Rev. Sci. Instr. 41, 423 (1970).

7. J.A. Simpson, "High Resolution, Low Energy Electron Spectrometer", Rev. Sci. Instr. 35, 1698 (1964);
C.E. Kuyatt and J.A. Simpson, "Electron Monochromator Design", Rev. Sci. Instr. 38, 103 (1967);
H. Boersch, J. Geiger and H. Hellwig, "Increasing the Resolution in Electron Energy Analysis" (in German), Phys. Letters 3, 64 (1962);
H. Boersch, J. Geiger and W. Stickel, "The Resolution of the Electrostatic-Magnetic Energy Analyzer", (in German), Z. Physik 180, 415 (1964).

8. In elastic scattering experiments it is not only the monochromator performance which determines the energy resolution obtainable, but also the Doppler broadening. The latter is proportional to the square-root of the electron energy. For example, in 20 eV scattering from a room-temperature helium gas target, the Doppler width is 17 meV. Thus crossed-beam experiments must be considered for obtaining higher resolution.

range, high-resolution experiments on electron scattering from atoms and molecules are lacking. (In some experimental papers curve plots down to zero energy are given, but no claim is made that the results near zero are meaningful.)[9]

Apparently the same technical problems which make it difficult to perform beam experiments at very low energies also limit the performance of the state-of-the-art electron monochromators.[10] These problems are: reduction of intensity due to space-charge limitation, increased sensitivity to magnetic stray fields and rf interference, beam loss due to surface charges which build up on insulating films, and -- perhaps most significantly -- beam loss due to electric stray fields resulting from work-function inhomogenieties across metal surfaces, the so-called patch effect.

It is this low energy region, down to about 10 meV, which is the topic of our research program. Our goal is to perform total cross section measurements with high energy resolution, employing a time-of-flight technique.

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9. For example, J.B. Hasted and A.M. Awan, "Resonance scattering of electrons by diatomic molecules", J. Phys. B, Ser. 2, 2, 367 (1969).

10. Even the best electron monochromators are not limited by principal effects such as electron diffraction on the monochromator entrance slit. The energy resolution of current-design monochromators is at least two orders of magnitude away from the diffraction limit.

Work is underway in another laboratory to extend Ramsauer-type measurements[11] down to an energy of 30 meV.[12] Aside from that, the only experimental access to the milli-eV range is through swarm (drift-tube) experiments.[13] Since the electrons in swarm experiments have a broad energy distribution, the results obtained correspond to averages over the energy distribution. To some extent the energy distribution can be "unfolded" in the data analysis. In this way it is possible to find out whether the cross section is constant over the whole range or slowly varying.[13,14] However, pronounced structure in the cross-section curve, such as resonances, cannot be determined in swarm experiments.

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11. The Ramsauer technique (C. Ramsauer, Ann. Physik 66, 546 (1921)) has been used in cross-section measurements by D.E. Golden and H.W. Bandel. "Absolute Total Electron-Helium Scattering Cross Sections for Low Electron Energies", Phys. Rev. 138, A14 (1965).

12. Private communication with Dr. T.L. Churchill, United Aircraft, East Hartford, Connecticut;
R.H. Bullis, T.L. Churchill and W.J. Wiegand, "Determination of the Electron-Helium Total Scattering Cross Section by Beam Techniques over the Entire Energy Range from 0.05 to 3.0 eV", Bull. Am. Phys. Soc. 14, 251 (1969).

13. R.N. Varney and L.H. Fisher, "Electron Swarms", Chapt. 6.1 in Methods of Experimental Physics, Vol. 7B, B. Bederson and W.L. Fite eds., Academic Press, New York 1968, p. 29.

14. J.L. Pack and A.V. Phelps, "Drift Velocities of Slow Electrons in Helium, Neon, Argon, Hydrogen and Nitrogen", Phys. Rev. 121, 798 (1961);
L.S. Frost and A.V. Phelps, "Rotational Excitation and Momentum Transfer Cross Sections for Electrons in H_2 and N_2 from Transport Coefficients", Phys. Rev. 127, 1621 (1962);
A.G. Engelhardt and A.V. Phelps, "Elastic and Inelastic Collision Cross Sections in Hydrogen and Deuterium from Transport Coefficients", Phys. Rev. 131, 2115 (1963);
A.G. Engelhardt, A.V. Phelps and C.G. Risk, "Determination of Momentum Transfer and Inelastic Collision Cross Sections for Electrons in Nitrogen Using Transport Coefficients", Phys. Rev. 135, A1566 (1964);
R.W. Crompton, D.K. Gibson and A.I. McIntosh, "The Cross Section for the J=0→2 Rotational Excitation of Hydrogen by Slow

Our experimental method is based on electron time-of-flight measurements. Electrons of 10 to 500 meV energy have velocities ranging from 6 to 42 cm/μsec. Since timing with an accuracy of several nanoseconds is easily possible with modern electronics, time-of-flight measurements appear to be very suitable for determining the energy of slow electrons. In reality, other technical problems are much more severe than timing. Two earlier experiments on electron time-of-flight spectroscopy[15,16] have not led to new scientific results, but we are convinced that the problems are technical rather than principal in nature, and that they can be overcome.

For three years, our work has been concerned with feasibility studies on time-of-flight techniques, design and construction of a major experimental apparatus, building and testing of electron-optical components and preliminary experiments on beam gating. Now we are very close to performing experiments with milli-eV electrons.

Our first measurements are aimed at observing the rotational resonances in molecular hydrogen, predicted by

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15. G.C. Baldwin and S.I. Friedman, "Time-of-Flight Electron Velosity Spectrometer", Rev. Sci. Instr. 38, 519 (1967).

16. M.Y. Nakai, D.A. LaBar, J.A. Harter and R.D. Birkhoff, "Nanosecond Time-of-Flight Studies of Electrons", Rev. Sci. Instr. 38, 820 (1967).

Frommhold,[17] of, if they cannot be found, establishing a lower limit for the interaction cross section. These resonances were predicted on the basis of anomalous observation in swarm experiments. A theoretical model has been given by Kouri.[18] The theoretical interpretation of these predicted resonances is based on a modification of the Lane-Geltman interaction potential.[19] The validity of this interpretation is being debated.[20] But even a negative result in the search for these resonances would be of value, because it would direct the attention again to the anomalies observed in drift-tube experiments which then would have to be explained in some other way.

After the measurements on H_2 we had planned to perform high-resolution measurements on N_2, O_2, CO_2 and other molecules, and to look for low-lying resonances in scattering from rare-gas atoms.

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17. L. Frommhold, "Resonance Scattering and the Drift Motion of Electrons through Gases", Phys. Rev. 172, 118 (1968); D.J. Kouri, W.M. Sams and L. Frommhold, "On the Possible Existence of Low-Energy Molecular Resonance States in Electron Scattering", Sixth International Conference on the Physics of Electronic and Atomic Collisions, July-August 1969, Cambridge, Mass. Abstracts, p. 153.

18. D.J. Kouri, "Rotational Resonances in Electron-Diatom Scattering", J. Chem. Phys. 49, 5205 (1968).

19. N.F. Lane and S. Geltman, "Rotational Excitation of Diatomic Molecules by Slow Electrons: Application to H_2", Phys. Rev. 160, 53 (1967).

20. Private communication with several theoretical atomic physicists, in particular, with Dr. N.F. Lane of Rice University.

Finally it is worth mentioning that this research program, aimed at measuring fundamental properties of atoms and molecules, could also provide data of interest in chemistry. Properties of free negative ions[21] and electron affinities of atoms and molecules[22] are important parameters in chemistry. Experimental work on resonance scattering of electrons has contributed substantially to a better theoretical understanding of negative ions and to new developments in quantum chemistry.[2,23] Additional information could be obtained from high-resolution measurements in the milli-eV energy region, not only about transient negative ions but perhaps also about stable negative ions of very small binding energy (that is, small but positive electron affinity of the neutral species). For binding energies on the order of a few milli-eV, an anomalous energy dependence of the scattering cross section might be observable near zero electron energy.

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21. R.S. Berry "Small Free Negative Ions", Chemical Reviews 69, 533 (1969).

22. B.L. Moiseiwitsch, "Electron Affinities of Atoms and Molecules", Adv. in Atomic and Molecular Physics 1, 61 (1965).

23. R.S. Berry, "Electronic Spectroscopy by Electron Spectroscopy", Ann. Rev. Phys. Chem. 20, 357 (1969);

A. Golebiewski, "Quantum Theory of Atoms and Molecules", Ann. Rev. Phys. Chem. 18, 353 (1967), in particular, the Section on "Quantum Chemistry and Scattering", p. 368;

P.G. Burke, "Resonances in Electron Scattering by Atoms and Molecules", Adv. Atomic and Molecular Phys. 4, 173 (1968).

3. Description of the Experiment

The experiment is performed on an electron-optical bench, about 40" long, housed in a bakeable ultra-high vacuum system. Over the length of the bench the magnetic field does not exceed 2 milligauss. Ample electric leads and feedthroughs are provided for controlling a large number of experimental parameters. Coaxial leads are used for currents and rf. All components of the experiment, set up on the electron-optical bench, are built in modular form by using prefabricated and largely standardized metal and ceramic parts. Care is taken to provide rf-tight shielding for all of the electric circuitry and to avoid grounding loops.

A 200-eV electron beam is gated (chopped) by sweeping across an aperture. This produces electron pulses of 5 to 10 nsec width with a repetition frequency of 100 to 200 kHz. The electrons are then decelerated over a very short distance and enter the milli-volt time-dispersion region, which each electron traverses with a flight time T, characteristic of its energy. At the end of the milli-volt region the electrons are accelerated to 200 eV and detected by a Channeltron electron multiplier. The pulse from the Channeltron is amplified and shaped. The time elapsed between gate pulse and Channeltron pulse (minus a constant electronic delay time and a constant electron flight time through regions where the electron energy is 200 eV) gives the flight time, T, which is characteristic of the electron energy in the milli-volt region.

The milli-volt region also contains the gas target. The pumping speed of the vacuum system is high enough to maintain a pressure differential between target chamber and the rest of the system.

Electron scattering in the target chamber reduces the number of electrons which reach the detector. The energy dependence of the scattering cross section shows up as a difference in the flight-time distribution spectrum without and with gas in the target chamber. Resonances will show up as pronounced structures in the spectrum.

Within the accuracy limited by the small but finite deceleration and acceleration regions, and curvature of the electron trajectories, the observed flight time T is an absolute measurement of the electron energy. Thus no energy calibration is needed.

It is known, however, that gas inlet into the target chamber can change the contact potential of the metal surfaces which define the potential of the electron beam. We plan to eliminate difficulties arising from this effect by extending the target chamber over the whole length of the milli-volt region (so that we have only one critical potential to deal with) and by employing "spectrum shaping" as explained below.

In our experiment, the flight-time distribution spectrum is not in itself scientifically significant: only the differences due to scattering in the gas target are important. Thus the

spectrum can be shaped to suit the experimental needs. For cross section measurements one might like a spectrum which is almost flat and extends over a large time interval. On the other hand, for monitoring a change of contact potential one would like to have a narrow peak in the spectrum whose shift can then be taken as measure of the contact-potential change, providing a quantitative basis for compensating the potential change by biasing the target chamber accordingly.

Several means are available for spectrum shaping:

a). Variation of the potential difference between cathode and target chamber.

b). Employment of a small potential barrier at the beginning of the milli-volt region, small enough not to affect the flight time appreciably but large enough to insure a minimum energy of the electrons transmitted.

c). Variation of the energy spread introduced by the time-varying potentials of the gate. This can be done by varying the sweeping speed or by deviating from a symmetric arrangement of the voltages on the two opposite deflector plates of the gate.

d). Employing magnetic focusing in the milli-volt region which enhances the probability of transmission for electrons in a small velocity or flight-time interval.

For photographic recording of the time-of-flight distribution spectrum the Channeltron pulse is shaped into a needle pulse with rise and fall time of less than 10 nsec and displayed on the screen of an oscilloscope. The scope sweep is triggered by the rf applied to the gate. Thus the horizontal position of the pulse on the screen corresponds to the flight time. The needle pulses have a height equal to the vertical dimension of the scope screen. By reducing the scope beam intensity to a very low level and photographing the pile-up of about 300,000 pulses, it is possible to obtain a low-noise density distribution on the film which directly corresponds to the flight-time distribution spectrum. Note that only the differences in the spectrum obtained with and without gas in the target chamber are of importance; thus non-linearities in the photographic process can be tolerated to some extent. For very quick observations it is not even necessary to put the film into a densitometer. By placing a wedge-absorption filter in front of the scope, such that the absorption varies in vertical direction and using high-contrast film, one could obtain a black-white contour which corresponds to the flight-time spectrum.

The energy resolution obtainable in our experiment is limited by several effects which have a different dependence on the electron energy, E.

a) The uncertainty δT in the measurement of the flight-time, T, leads to a limit for the energy resolution which is proportional to $E^{3/2}$. In Figure 1 we give a log-log plot of energy resolution obtainable versus electron energy. The line labeled "δE_{timing}" represents the limitation due to δT = 5 nsec combined with a milli-volt region of length L = 30 cm.

b) The uncertainty in the length of the electron trajectory, L, introduced by the small but finite deceleration and acceleration regions and by focusing in the milli-volt region, leads to a limit for the energy resolution which is proportional to E. The line labeled "δE_{length}" represents this limitation and is based on the assumption that $\delta L = 0.01 \times L$.

c) The limitation due to Doppler effect in the room temperature gas target is given by

$$E_{Doppler} = 7.4 \text{ (meV)} \cdot \sqrt{\frac{E/volt}{A/amu}} ,$$

where A is the mass number of the target atom or molecule. Lines of $\delta E_{Doppler}$ are shown in Figure 1 for H, H_2 and He.

d) Finally, one has to consider a variety of effects, such as rf interference and hidden thermoelectric potentials which might change with time, none of them of principal

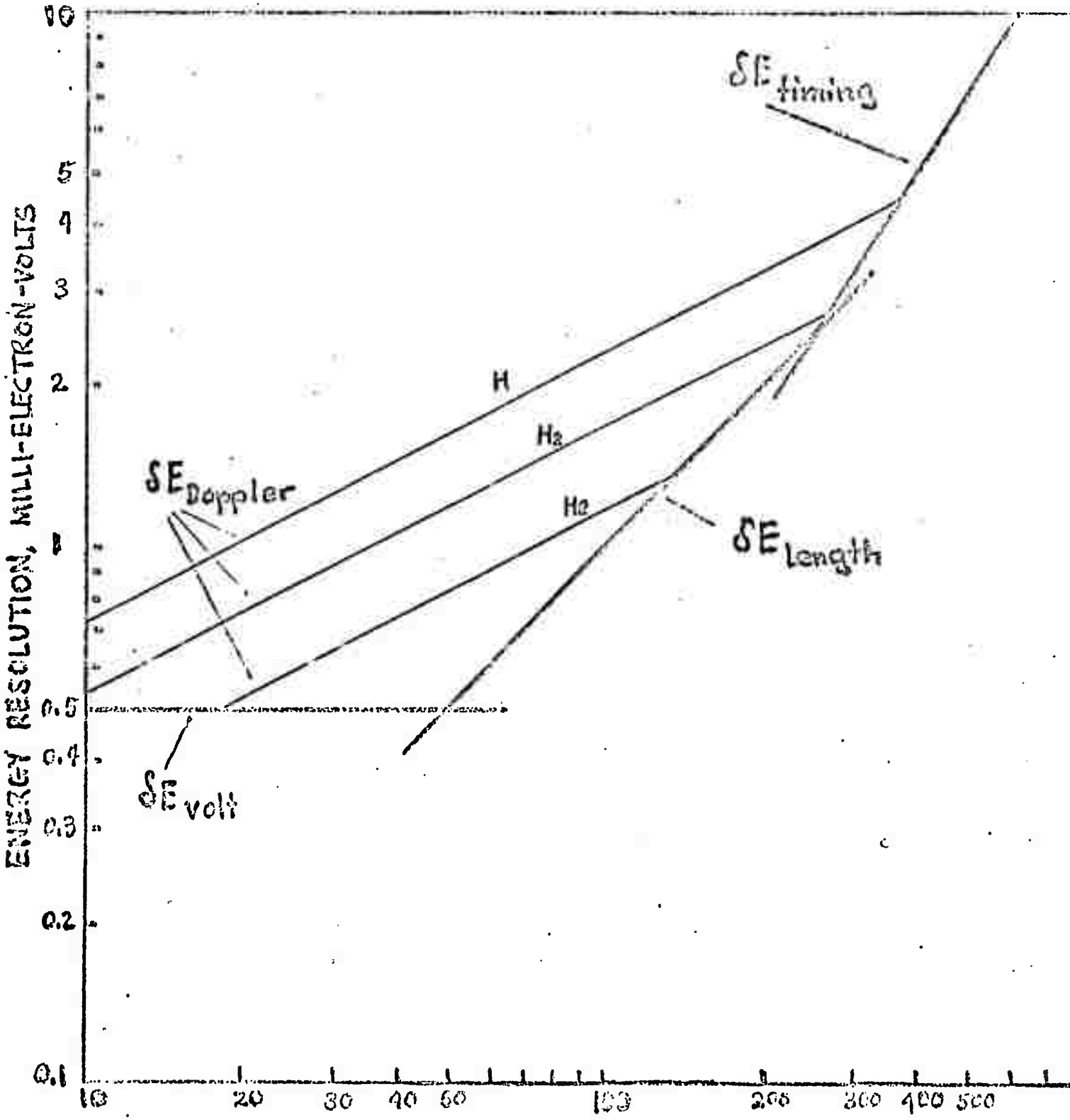

Fig.1 Energy Resolution obtainable in our experiment as a function of the electron energy. The lines drawn represent different resolution-limiting effects (explained in the text). At any given electron energy the highest-lying line determines the limitation.

nature. They are lumped together here in an uncertainty independent of the electron energy E. The line labeled "δE_{volt}" represents our conservative estimate of 0.5 meV as a limit in our present experiment.

At any given electron energy, E, the highest curve in Figure 1 represents the limiting effect. Note that for H_2 in the energy range from 10 to 250 meV, the limiting effect is Doppler broadening. For the heavier molecules (N_2, O_2, etc.) the Doppler broadening is much smaller and, therefore, the technical limitations apply. Of practical importance is the limit δE_{length} which indicates how much electron optics can be utilized without affecting the energy resolution. The line in Figure 1 is consistent with beam aperture angles as large as 0.1 rad, which is more than needed for increasing intensity and exercising spectrum shaping by electron-optical means.

Several experimental means are available for distinguishing real resonances in H_2 from "ghosts".

a) The location of the resonance structure on the flight-time scale must remain fixed when spectrum shaping is used.

b) Similar resonances at different energies (flight times) must be observed in D_2.

c) In measurements with para-hydrogen as a target, only every other resonance should occur since only rotational states with even quantum numbers, J = 0,2 ..., can be populated.

4. Description of the Experimental Apparatus

An electron-optical bench with highly standardized components was developed by H. Boersch[24] in 1951 for experiments with fast electrons (typically 30-50 keV). This solution of the technical problems with fast electrons has been very successful in a great variety of experiments including work on electron spectroscopy, electron diffraction and electron scattering.[25] For work with slow electrons the requirements for cleanliness (bakeable ultra-high vacuum) and magnetic shielding dictate a new technology. The system described here was developed with the aim of combining the versatility of the old electron-optical bench with an environment suitable for experiments with slow electrons.

In work with electrons of very low energy, the main technical difficulties arise from electric and magnetic stray fields. Electrostatic stray fields can be controlled by a careful selection of the materials used, and by producing a clean environment in a bakeable ultra-high vacuum system. Technical means for adequate magnetic shielding and rf shielding are also available.

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24. H. Boersch, Z. Physik 130, 513; 517 (1951).

25. H. Boersch, M. Miessner, and W. Raith, Z. Physik 168, 404 (1962); H. Boersch, W. Raith and H. Weber, Z. Physik 163, 467 (1961); W. Raith and R. Schliepe, Z. Physik 170, 185 (1962).

The problems in system design result from competing requirements; for example, enclosing the system completely with magnetic shielding materials versus providing openings for pumping and electric feedthroughs.

The system design was also influenced by economic considerations. Components which have to be developed and perhaps built in several versions of increasing sophistication should be as inexpensive as possible. The unavoidably expensive parts of the system--related to ultra-high vacuum, magnetic shielding, electric feedthroughs, control gauges and circuits--are designed such that they have to be built only once, and will accommodate all modifications and extensions of the experimental apparatus now foreseeable, without costly rebuilding.

These considerations led to the implementation of an electron-optical bench, on which the experiment is built up of several modules. All the hardware is permanently connected to the bench and its environment, which provides the bakeable vacuum, the magnetic shielding, and all the electric leads. The modules are relatively inexpensive, since they consist only of small, standardized metal and ceramic parts. Typical components are: an electron gun, a target chamber, an electron detector, a gate, and several immersion lenses and einzellenses.

Layout

The proposed experiments with electrons of extremely low energy require sophisticated techniques of electron optics, electronics, vacuum and magnetic shielding. An extremely clean ultra-high vacuum system is required. The magnetic field must be reduced to about 1/1000 of the earth's magnetic field. This very low magnetic field is most easily obtained by enclosing the whole experiment with magnetic shielding material. However, openings are required for the many electrical leads and for efficient gas pumping; therefore, evaluation of several compromise solution had been necessary.

The finally chosen design consists of a main vacuum chamber located on top of the pump stack containing flanges for vacuum gauges and electrical feedthroughs. The experiment will be performed on an electron-optical bench protruding from the main chamber as a horizontal arm. A stainless-steel cylinder sleeves the electron-optical bench, closing the vacuum system. The magnetic shields consist of two co-axial cylinders surrounding the vacuum cylinder.

Vacuum

In order to prevent oil contamination of the system from the rotary vacuum pump in the foreline, both a zeolite trap and a thermoelectric baffle are incorporated into the foreline. Following techniques established in this laboratory for producing clean, ultra-high vacuums, a mercury diffusion pump is used. A thermoelectrically-cooled baffle and a large liquid nitrogen trap assure that the

system is free of mercury vapor. All the vacuum equipment is connected to a safety-interlocked control which is designed to prevent all imaginable disasters.

The vacuum system is all metal and completely bakeable. The vacuum shell is built from type 316 stainless steel, chosen for its non-magnetic properties. The small flanges are conflat flanges with copper gaskets; the large flanges have flat surfaces and metal-wire o-ring seals. The chamber was demagnetized after machining by an appropriate heat cycle in a vacuum furnace.

Magnetic Shielding

Two coaxial magnetic shields are placed externally around the vacuum sleeve which fits over the electron-optical bench. They are demagnetized in place by a 1000-A alternating current flowing through the sleeve.

In addition to the coaxial cylinders an end cap of shielding material is used at the end opposite the main chamber and an external compensation coil is used near the main chamber. This provides the region of the electron beam both with good shielding and ultra-high vacuum. External shielding is preferred because it reduces the surface area inside the vacuum system, on which gases can adsorb. According to tests in our own laboratory, the shielding is adequate for the experiments with slow electrons.

Electric Leads

Each module on the electron-optical bench will have several wire leads which terminate on stand-off insulators on each side of the bench support arm; from these insulators, permanent leads go to the vacuum feedthroughs in the terminal chamber. Thus,

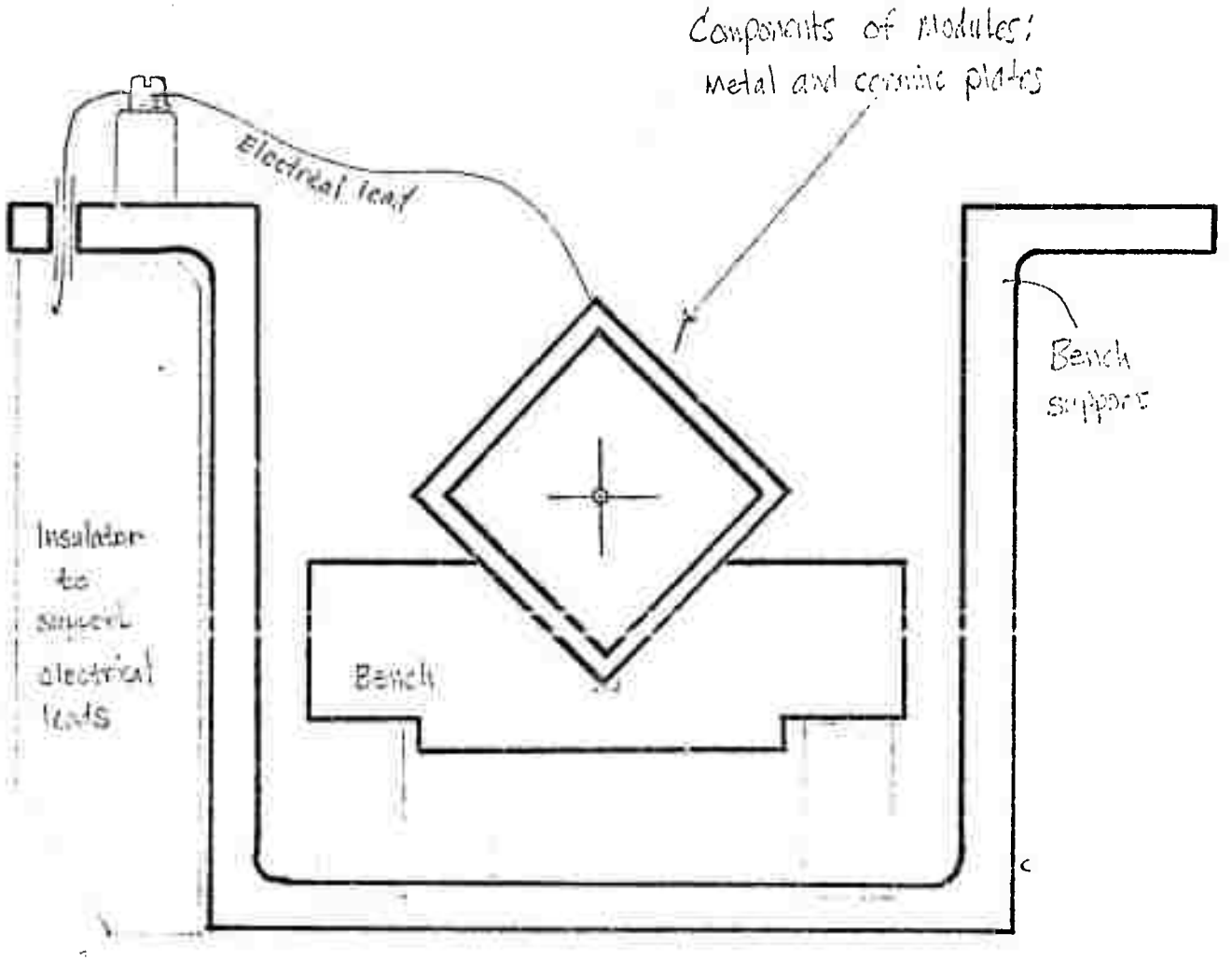
installation and removal of a module is quick and simple. Special shielded leads are used for connections to the gate and to the electron detector. At this time 40 electric leads plus several special coaxial lines are built in. If necessary, the system can easily accomodate 40 more leads.

Electron Optical Bench

The bench (see Fig. 2) consists of a solid block of aluminum with an accurately-machined right-angle v-groove. This provides good lateral mechanical alignment of all the modules: the modules can be taken in and out without tedious telescopic alignment procedures being necessary. The fine adjustment of the electron beam will be done with electrostatic beam deflection at several points along the beam. The bench itself provides a guarded ground potential; for that purpose, the bench is separated from the bench support by ceramic standoff insulators. In its present form, the bench is mounted on one arm protruding from the main chamber. The useful length of the bench, about 3 feet, should be sufficient for performing the proposed experiments. However, if necessary for some future experiment, the system can be extended by adding another chamber to the other side of the main chamber and by leading the beam from one arm through the main chamber into the other chamber. (In this case, an internal magnetic shield inside the main chamber would be used).

Bakeout

An oven (heating power 4 kW) which can enclose the whole system is hung from the ceiling using pulleys on counter



CROSS-SECTION OF ELECTRON-OPTICAL BENCH

FIG. 2

weights. Bakeout up to 400°C is easily possibly this way. During bakeout the magnetic shielding cylinders and the cart are removed.

Testing of Electron-Optical Components

As mentioned above, the components are built by simply combining metal plates and tubes with prefabricated ceramic insulators. The first components built this way are an electron gun (utilizing a Philips dispenser cathod), various lenses, and an arrangement for studying focusing of low-energy electron beams. The latter one consists of a mesh to be placed where the beam profile is to be observed. Electrons penetrating the mesh are accelerated to about 10 keV. With an immersion lens system the mesh is imaged onto a luminescent screen. The image is observed through an end window in the vacuum sleeve. This test system has proved extremely useful for developing various electron-optical components.

5. Summary

The whole system described above is operational. The electron detection system works. We have gated a 200-eV beam and solved all the gate-related problems. The external electric circuits are all contained in an rf-tight housing for shielding against interference from radio stations and other experiments.

We do not know yet how many problems will be encountered before reliable high-resolution measurements of flight-time distribution spectra are obtained. But the system is ready for exploring and solving those problems.

Final Technical Report for Period Ending

June 30th 1970

Contract N 0014-67-A-0097-0008

"Research on Dissociation of Molecular Hydrogen

Leading to Formation of Metastable Hydrogen Atoms"

TASK II

(a). Introduction

Dissociative excitation of molecular hydrogen by electron bombardment may take place according to the equation

$$e + H_2 \rightarrow e + H(1S) + H(2S)$$

in which one of the products is a metastable hydrogen atom, H(2S). This reaction has been studied and utilized by various research workers. The work here reported follows the pioneering investigation undertaken at Yale by Leventhal, Robiscoe, and Lea (Physical Review 158, 49 (1967). In that research, here referred to as LRL, the metastable H(2S) atoms were produced in an electron gun by electron bombardment of low pressure molecular hydrogen gas. The H(2S) atoms were detected by the process of electrostatic quenching. In this process an electric field admixes some H(2P) wave function into the H(2S) state wavefunction, so that the metastable atom decays to the ground state, H(1S). The optical decay radiation, of wavelength 1216 Å (Lyman-alpha line 2P → 1S) was detected by a photomultiplier. The pulses of photo current were counted, affording a measure of the H(2S) atoms being quenched. The LRL work studied the distribution of velocities of H(2S) atoms emitted at right angles

to the direction of electron bombardment. The electron gun was pulsed on briefly, and the 'time of flight' of the H(2S) measured. Knowing the length of the flight path, the distribution of velocities was readily inferred from the distribution in arrival times. The main features of the velocity distribution observed by LRL were (i) a group of H(2S) atoms with an average velocity of 8.3×10^5 cm/sec, designated "slow" metastables, and (ii) a group of atoms with average velocity 3×10^6 cm/sec, designated "fast" metastables, which appeared when the energy of the incident electrons was raised some 10 eV above the threshold for the slow metastables. The slow and fast atoms were interpreted as arising from attractive and repulsive energy states to which the molecule could be excited by electron bombardment, prior to dissociating.

The research reported here is essentially a continuation and extension of the LRL work. This report describes the developments that have taken place in the last twelve months.

(b) Review of the past year's work

The renovated LRL apparatus has been maintained in operation, and has served as a testing ground for some of the new developments that are being incorporated in the new apparatus (Mk II), (Fig. 1). The operation of the original LRL vacuum system has proved to be rather troublesome, however, underlining the need for the Mk II version. Aside from difficulties of obtaining good vacuums, this equipment twice suffered internal water leaks, causing some damage and delay. While in working order, several time-of-flight spectra

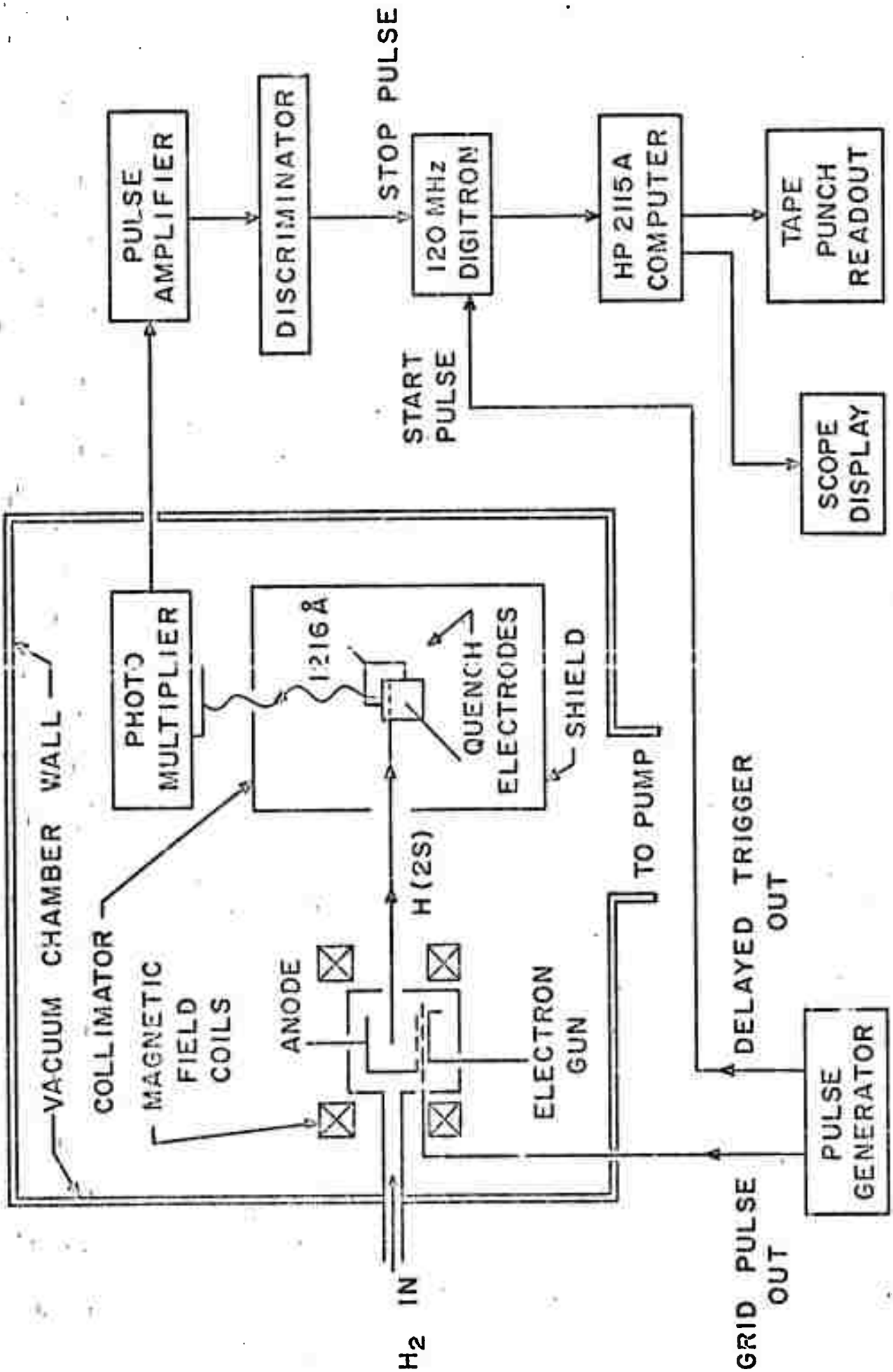


Fig. 1 Schematic of the Mk-II time-of-flight apparatus.

of H(2S) atoms were recorded (Fig. 2), which seemed to show signs of additional structure in the "slow peak" - viz, a hint of a double peak in what had previously been taken to be a single-peaked distribution. Because the equipment has been subject to low and erratic count rates, it has not proved possible to establish this feature unambiguously. Hopefully the Mk II apparatus will be superior in counting statistics, and so enable this point to be clarified. The implication of distinct peaks in the slow velocity distribution is that more than one excited molecular potential curve is involved in the dissociation process. It is premature to speculate on the identity of such levels at the present time. In all other respects, the gross velocity distribution spectra were no different from those reported by LRL, who noted that the absence of slow metastables (with velocities less than 4×10^5 cm/sec.) was not in accord with a theoretical prediction of Harriman (Ph.D. thesis, Stanford University, 1956). The source of this discrepancy remains unidentified. If the Mk II apparatus confirms the earlier experimental results, it will provide further stimulus to attempts to understand this discrepancy.

The large new stainless steel vacuum chamber and pumping system have been assembled and leak checked. We have measured ultimate pressures of 10^{-8} torr, with the chamber empty. The use of mercury diffusion pumping, rather than oil pumping as in the LRL apparatus, should greatly diminish the oil contamination problem, which has adverse effects on electron gun operation.

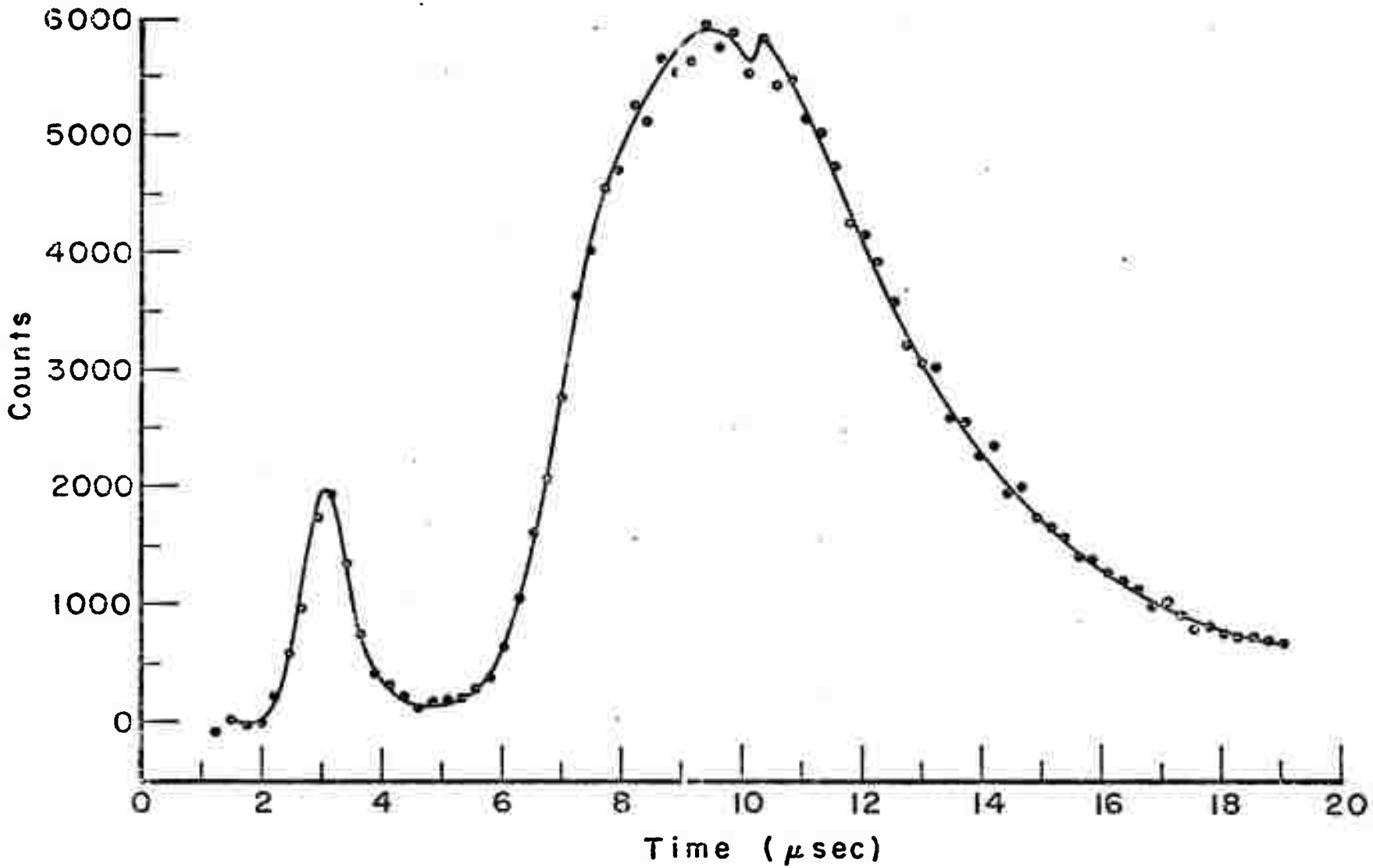


Fig. 2 Typical time-of-flight spectrum for metastable hydrogen atoms. Electron bombardment voltage was 50 volts. Flight path was 10 cm.

The electron gun and quench region to be installed in the new chamber contain a number of changes made in the light of experience with the original models. Thus the arrangement of the electrode structure of the gun has been redesigned. The direct electron beam, which traverses the bombardment region, is collected on an anode plate, which enables it to be monitored independently of the rest of the current collected by the walls and other boundaries of this region. This 'direct'current is a measure of the effective excitation current. By means of an integrator (which averages the current pulses) and a feedback loop, the cathode emission can be controlled in a way that maintains the excitation current constant. Previously, no regulation of the current had been attempted, with the result that substantial drifts occurred at times. An additional problem with the electron gun arose from the close proximity of the control grid to the anode. Due to capacitance between these two electrodes, when a short pulse was applied to the control grid to turn the gun on briefly, a similar pulse was detected on the anode. In the new design, an additional grid or shielding-electrode is incorporated between the control grid and the anode, so as to reduce this capacitive coupling. A further feature being taken into account in the new gun is the desirability of being able to rotate the axis of the gun, so as to study the angular distribution of the H(2S) atoms.

Considerable thought has also gone into the design of the "quench region", wherein H(2S) atoms are detected after traversing the flight path from the gun. From the point of view of obtaining

good precision in the atomic velocity, it is important that the detection region is well localized. A computer analysis of the spatial distribution of the electric fields produced by the quench electrodes of LRL has been undertaken. This shows that the field is not quite as well localized as we would wish. To circumvent this, we are introducing collimating slits between the electrodes and the photo-detector so as to define the detection region more precisely. We also recognise that there is a variation of quench efficiency with metastable velocity, since the slower-moving atoms spend a longer time in the field, and so are preferentially quenched. An experimental investigation of this dependence has still to be undertaken. As an alternative to this design of quench region, we have a different design which consists of two closely spaced pieces of metal mesh, maintained at different potentials, placed in the path of the beam so as to provide a localized electric field parallel to the direction of the metastable beam. A fraction of the decay photons, produced by the electric field quenching, would be detected by a photomultiplier placed at the side so as to view the space between the two gauzes. Yet one more detection scheme that suggests itself is the use of a Bendix Channeltron detector, one of which has been acquired for this purpose.

The electronic equipment is complete and ready for the first investigations with the new apparatus. The addition of an extra 4K memory unit to the Digital Computer has doubled its capacity. Some modifications have been made to the computer programs to expand the number of channels of data acquisition to 1000. When

final construction work on the electron gun and quench region is completed in our machine shop, we shall be all set to embark on a variety of molecular dissociation experiments which promise to contribute significantly to our understanding of molecular structure, especially of the excited molecular potential curves.