MASTER

CROSS SECTIONS AND EQUILIBRIUM FRACTIONS
OF D^+ AND D_2^+ IONS IN METAL VAPORS

Project Progress Report for the Period
June 1, 1976 to February 1, 1978
Department of Energy Contract EY-76-S-02-4022

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or timeliness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights.

Submitted by Thomas J. Morgan
Assistant Professor of Physics
Wesleyan University
Middletown, Ct. 06457

ABSTRACT

The purpose of this program is to measure cross sections and equilibrium fractions of D^+ and D_2^+ ions in metal vapors. In particular, in connection with double charge exchange D^- ion sources, we are concerned with D^- formation in alkaline-earth vapor targets. Also, in connection with possible metal vapor contamination in the system, we are concerned with cross sections for high energy D^+ , D^0 and D^- collisions with these metal vapors. Results from this research will fill in a gap in our knowledge of single and double charge transfer and multiple collision processes in alkaline-earth targets. During the period covered in this report we have completed construction of the apparatus necessary to carry out the program and have measured cross sections and equilibrium fractions for $D^+ + Mg$ and $D^+ + Ba$ collisions.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED *EB*

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

DISCUSSION OF PROGRESS

The first six months of the contract period were devoted to final apparatus design and procurement. Vacuum components were purchased and installed. Particle detectors and the metal vapor target were designed and built. After installation of all experimental components, and ultimate vacuum obtained in the apparatus (2×10^{-7} torr), a series of experiments using argon gas were performed to test the reliability of our equipment and experimental technique. Cross sections in argon were measured and good agreement with previously published results was obtained. Before beginning our study of metal vapors it was necessary to perform tests on the target oven to ensure that we could measure the temperature of the cell accurately. These tests involved melting lead in the cell and determining the cell temperature reading corresponding to the melting point of lead. After completion of these tests we began our study of metal vapor targets with magnesium.

Magnesium was chosen for several important reasons: (1) It is the only alkaline-earth target for which cross section data is available. In particular, the cross section for single electron capture, σ_{10} , in $D^+ + Mg$ collisions has been measured by three groups¹⁻³ with reasonably good agreement existing and so it served as a final test of our apparatus and cross section measuring techniques. (2) A serious discrepancy in magnitude existed between the only two previous measurements of the double electron capture cross section, σ_{1-1} ^{2,4} (3) Theoretical predictions⁵ indicated σ_{1-1} should increase down to ~ 200 ev whereas experimental data showed a maximum at about 7 keV.²

No unforeseen difficulties arose and a complete set of data for σ_{10} and σ_{1-1} was obtained over the D^+ energy range from 2 to 180 keV and reproduced several times over a period of a few months. (The results of

Discussion of Progress

-3-

these measurements will be discussed in the next section.) During this time a retarding grid energy analyzer was built and a complete study of the beam energy as a function of accelerator parameters was performed. This was necessary in order to ensure reliable knowledge of the energy of the beam at the low energy end of our measurements. Also during this time several tests were performed to assure that all particles were collected. (These tests involved changing the size of the exit aperture of the oven.) We had originally intended to next look at either sodium or rubidium. However, calculations at that time by Hiskes⁶ indicated that the heavier alkaline-earths would be much more attractive as a charge exchange target than sodium or rubidium. Consequently, we decided to use barium. (Similar conclusions have recently been reached by Il'in⁷).

Several experimental difficulties were encountered with the use of barium. After several days of operation we discovered that barium at high temperatures reacts with copper. As a result we had to modify our system and use stainless steel gaskets in the oven. After the modifications were complete cross section data were taken for several weeks. During this time it was observed that the data when retaken were always slightly ($\sim 10\%$) lower than the previous measurement. This was eventually attributed to impurities which we tried to eliminate by baking the oven at high temperatures for several days. This procedure did not work and our remeasured cross sections were again lower. We finally were able to obtain 99.9% pure barium (as compared with 99.5% previously used) by special order. With the new purer barium the results were reproducible. A complete set of cross section data was taken over the D^+ energy range from 3 to 180 keV and reproduced over a period of several weeks.

After completion of the barium cross section measurements we decided to measure equilibrium fractions. To avoid difficulties associated with the broad angular distribution of the beam emerging from thick targets we placed a collimator between the oven and the analyzing electric field. This ensured that the charge — analyzed beams fell within the detectors. This technique was first used quite recently by the LBL group and as they have noted⁸ could cause serious errors in cross section measurements but should be satisfactory for equilibrium yields. To investigate the reliability of this approach we measured the equilibrium yields in argon and helium gas. In both cases we have extended available data to both higher and lower energies and where the data overlap good agreement exists. Our results for the equilibrium yields in magnesium are in good agreement with the results of the LBL group.⁹ We have recently switched to barium and, as in the cross section measurements, several experimental difficulties have arisen. Temperatures required to reach equilibrium in the case of barium are quite high compared to other metal vapors. (Temperatures greater than 1000 K are required.) We have burned out several heaters and plugged our apparatus with barium. Several experimental procedural modifications have been employed to eliminate these problems and we are now taking equilibrium yield measurements with barium. A limited amount of preliminary data now exists and we plan to complete these measurements before the end of the present contract period.

DISCUSSION OF RESULTS

σ_{10} in Mg

We have measured σ_{10} in Mg over the D^+ energy range from 2 to 160 keV.

Discussion of Results

-5-

Previous data were available over the range from 8 to 160 keV^{1,2,3}. The present results agree well with previous work. As a consequence of our measurements, Olson¹⁰ has performed a low energy (<20 keV) Landau-Zener calculation and a high energy (>60 keV) Monte Carlo calculation for σ_{10} in Mg. The agreement is good except at the lower energies (<10 keV).

σ_{1-1} in Mg

In this case there are two previous measurements. Futch and Moses² have measured σ_{1-1} over the range 8 to 80 keV and Il'in⁴ has obtained data over the range 20 to 160 keV. These two measurements disagree by as much as a factor of ten in absolute value. Our results from 2 to 160 keV agree very well with those of Futch and Moses. The cross section exhibits interesting structure at energies lower than previously measured. There is a maximum at 7 keV followed by a minimum at 2.8 keV. For lower energies the cross section is rising. This behavior below 2.8 keV is in qualitative agreement with predictions of Olson,⁵ however, the calculated cross section is a factor of seven higher than our measured results. The reasons for the structure in σ_{1-1} and the large discrepancy between theory and experiment are being pursued and, in collaboration with Olson, a model based on two different D^- production and loss mechanisms, is being explored.

σ_{2s} in Mg

Although not part of the research contract proposal we are also measuring the cross section for metastable deuterium formation, σ_{2s} . Measurements of this cross section have been completed over the D^+ energy range from 10 to 160 keV. These results are the first absolute measurements of $D(2s)$ formation cross sections in alkaline-earth metal targets.

Discussion of Results

-6-

F_{∞}^{-} , F_{∞}^{+} , F_{∞}^0 in Mg

We have measured equilibrium yields in Mg over the limited D^{+} energy range from 4 to 8 keV and our results agree well with those of the LBL group.⁹

σ_{10} in Ba

The cross section for single electron capture in Ba has been measured over the D^{+} energy range from 4 to 180 keV. The maximum value of the cross section is $3 \times 10^{-15} \text{ cm}^2$ at 8 keV compared with $2 \times 10^{-15} \text{ cm}^2$ at 14 keV in Mg. This behavior is in agreement with the adiabatic criteria. As the energy increases σ_{10} in Ba decreases much slower than in Mg and the energy dependence possibly indicates evidence for inner shell electron capture for energies greater than about 60 keV. For example, at 140 keV σ_{10} in Ba is $1 \times 10^{-16} \text{ cm}^2$ and in Mg is $2 \times 10^{-17} \text{ cm}^2$.

σ_{1-1} in Ba

The cross section for double electron capture in Ba has been measured over the D^{+} energy range from 4 to 180 keV. The maximum value of σ_{1-1} in Ba is $8 \times 10^{-18} \text{ cm}^2$ at 10 keV compared with $3.5 \times 10^{-17} \text{ cm}^2$ in Mg. This clearly indicates that energy balance is not the main factor in determining the magnitude of the cross section. Level crossing associated with the attractive coulomb potential of the exit channel appears to dominate in the collision at lower energies. At higher energies the comparison between Mg and Ba is reversed. σ_{1-1} in Ba falls off very slowly with increasing energy in comparison to Mg indicating possible inner shell capture. For example, at 100 keV σ_{1-1} in Ba is $1 \times 10^{-18} \text{ cm}^2$ and σ_{1-1} in Mg is $5 \times 10^{-20} \text{ cm}^2$.

Discussion of Results

-7-

σ_{2S} in Ba

Measurements of this cross section have been completed over the D^+ energy range from 3 to 180 keV. The ratio of our measured cross sections $(\sigma_{10}/\sigma_{2S})^{-1}$ yields the fraction of the D^0 beam in the metastable 2S state after the target. For energies less than 14 keV Ba produces a larger percentage of D(2s) atoms than Mg. For energies between 14 and 120 keV Mg is more efficient. And for energies greater than 120 keV the D(2s) fraction in the D^0 beam is the same for Mg and Ba targets.

$F_{\infty}^{-}, F_{\infty}^{+}, F_{\infty}^0$ in Ba

We are presently measuring the equilibrium yields in Ba and have preliminary data over a limited energy range. These measurements will be finished by the end of the present contract period (June 1, 1978).

REFERENCES

Reprints, Preprints + Abstract
removed

1. K.H. Berkner, R.V. Pyle and J.W. Stearns, Phys. Rev. 178, 248 (1969).
2. A.H. Futch, Jr. and K.G. Moses, Abst. of V ICPEAC; Int. Conf. on the Phys. of Elect. and Atom. Coll. (Nauka, Leningrad, 1967), p. 12.
3. R.N. Il'in, V.A. Oparin, E.S. Solov'ev and N.V. Fedorenko, JETP Letters 2, 197 (1965).
4. R.N. Il'in, V.A. Oparin, I.T. Serenkov, E.S. Solov'ev and N.V. Fedorenko, Abst. of VII ICPEAC; Int. Conf. on the Phys. of Elect. and Atom. Coll. (Amsterdam, Holland, 1971), p. 793.
5. R.E. Olson, Phys. Lett. 55A, 83 (1975).
6. J.R. Hiskes, Lawrence Livermore Laboratory Report UCID - 853 (1975).
7. R.N. Il'in, Abst. of International Symposium on Negative Ion Formation (Moscow, 1977).
8. K.H. Berkner, D. Leung, R.V. Pyle, A.S. Schlacter and J.W. Stearns, to be published in Phys. Lett. A.
9. K.H. Berkner, D. Leung, R.V. Pyle, A.S. Schlacter and J.W. Stearns, Nucl. Instrum. Methods 143, 157 (1977).
10. R.E. Olson, private communication.

act₇

TRAVEL DURING CONTRACT PERIOD

1. * July 1976 - LBL - collaboration
2. December 1976 - University of Nebraska - atomic physics meeting (DEAP)
3. July 1977 - Paris, France-X ICPEAC- (Barium cross sections reported.)
4. * September 1977 - Brookhaven - Negative Ion Symposium (D^- formation in barium and magnesium reported.)
5. December 1977 - University of Tennessee - atomic physics meeting (DEAP) (Magnesium cross sections reported.)
6. * May 1978 - LBL - collaboration
7. Several visits to ORNL - Fusion Data Center Work.

* Travel supported by present contract.

PERSONNEL INVOLVED WITH PROJECT

1. Frederick Eriksen (Sept. 1976-Aug. 1977) - Postdoctoral researcher supported by Wesleyan University. He is now Assistant Professor of Physics at University of Southern Mississippi
2. James Kurose (Jan. 1977-Present) - undergraduate student
3. David Mariani (Jan. 1976-June 1977) - undergraduate student presently doing graduate work at Yale University
4. Marguerite Mayo (Jan. 1977-Present) graduate student
5. Jack Stone (Jan. 1978-Present) - Postdoctoral researcher supported by present contract.

PUBLICATIONS DURING CONTRACT PERIOD

The following publications are attached:

1. Charge Exchange Cross Sections in Proton-Barium Collisions (X ICPEAC)
2. Single and Double Electron-Capture Cross Sections for $H^+ + Mg$ Collisions (DEAP Meeting)
3. D^- Formation by Double-Electron Capture in Alkaline-Earth Targets: Recent Results (Symposium on the Production and Neutralization of Negative Hydrogen Ions and Beams)
4. Double Electron Capture in $H^+ + Mg$ Collisions (submitted to Physics Letters A)