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REPORT NO. 1398

USE OF IONIC MOBILITIES FOR  
MEASUREMENTS IN THE LOWER IONOSPHERE

by

George E. Keller

May 1968

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Aberdeen Proving Ground, Md.  
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ABSTRACT

The results of recent laboratory investigations indicate that attempts to use ionic mobilities for the identification of positive ions in the lower ionosphere must necessarily fail. A mobility determination requires ion-molecule collisions; chemical reactions occurring during these collisions will cause each mobility spectrum to tend toward a continuum. Because these reactions do not change the total number density of ions, conductivity measurements can be made using an average mobility for ions in air.

TABLE OF CONTENTS

	Page
ABSTRACT . . . . .	3
I. INTRODUCTION . . . . .	7
II. RESULTS OF LABORATORY MEASUREMENTS . . . . .	8
III. EVALUATION OF RECENT LABORATORY MEASUREMENTS . . . . .	13
IV. EFFECT OF LABORATORY FINDINGS ON <u>IN SITU</u> MEASUREMENTS . . . . .	16
V. ACKNOWLEDGMENTS . . . . .	18
BIBLIOGRAPHY . . . . .	19
DISTRIBUTION LIST . . . . .	21

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## I. INTRODUCTION

Recently, there have been published several suggestions that ionic mobilities be used in lower ionospheric measurements of ion identification and concentration, total ion concentration, and conductivity (Hoult and Kuo, 1967; Hoult and Kuo, 1966; Hoult, 1965; Hale, 1966; Dolezalek, Oster, Coroniti, and Mester, 1966; Dolezalek, 1962). The purpose of this paper is to investigate the effect that ion-molecule reactions will have on the proposed in situ measurements in light of recent laboratory findings.

When ions of a given type drift in a gas under the influence of a static, uniform electric field they lose energy in (elastic) collisions with the gas molecules and gain energy from the electric field between collisions. If the energy acquired by the ions between collisions is small compared with their mean thermal energy, their mean drift velocity,  $v_d$ , in the direction of the electric field will be proportional to the field strength,  $E$ ,

$$v_d = KE. \quad (1)$$

The constant of proportionality,  $K$ , is called the mobility of these ions in the particular gas. If  $E$  is increased to the extent that the energy acquired by the ions between collisions becomes larger than their mean thermal energy,  $K$  is no longer a constant.

It should be clearly understood that ion-molecule collisions are absolutely essential to the mobility measurement, for without frequent collisions the ions of interest would quickly acquire "field" energies far in excess of their thermal energies.

For ease of comparison, a mobility quoted in the literature is usually a "reduced mobility,"  $K_o$ , where

$$K_o = K \frac{p}{760} \frac{273}{T}. \quad (2)$$

Here,  $p$  and  $T$  are the gas pressure and the temperature, respectively, at which the measurement was performed. Quoted values of reduced

mobilities usually, but not always, refer to mobilities measured or calculated for the field low enough to insure that  $K_0$  has become constant. It can be shown (McDaniel, 1964) that the ratio  $E/p$  is the parameter which determines the mean energy that the ions will acquire from the electric field between collisions. Mobilities are usually plotted versus  $E/p_0$ , where

$$p_0 = p \frac{273}{T}, \quad (3)$$

to take into account the variation of the number density of the gas with respect to temperature. (See McDaniel, 1964, for a more complete discussion of mobility concepts, theories, and measurements.)

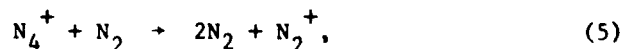
## II. RESULTS OF LABORATORY MEASUREMENTS

The concept of mobility for ions drifting in a gas and undergoing only elastic collisions has been verified and is well documented. For example, it has been found that the measured drift velocities of noble gas ions (Hornbeck, 1951) and of alkali ions (Tyndall, 1938) drifting in a noble gas under the influence of a weak electric field did indeed approach a constant value as  $E/p$  was decreased.

The effect of reactions on mobility measurements first came to light in work on molecular gases. Varney found that in both carbon monoxide and nitrogen (Varney, 1953) the drift velocity versus  $E/p_0$  curves had a pronounced, unexpected knee. His nitrogen results are reproduced as Figure 1. He postulated that this unusual behavior was due to reactions between two positive ions in nitrogen,  $N_2^+$  and  $N_4^+$ . He suggested that at low values of  $E/p_0$  a reaction forming  $N_4^+$  from  $N_2^+$ ,



would dominate so that the drift velocity measured should be that expected for  $N_4^+$  in  $N_2$ . Similarly, he suggested that at high values of  $E/p_0$  a reaction forming  $N_2^+$  from  $N_4^+$ ,



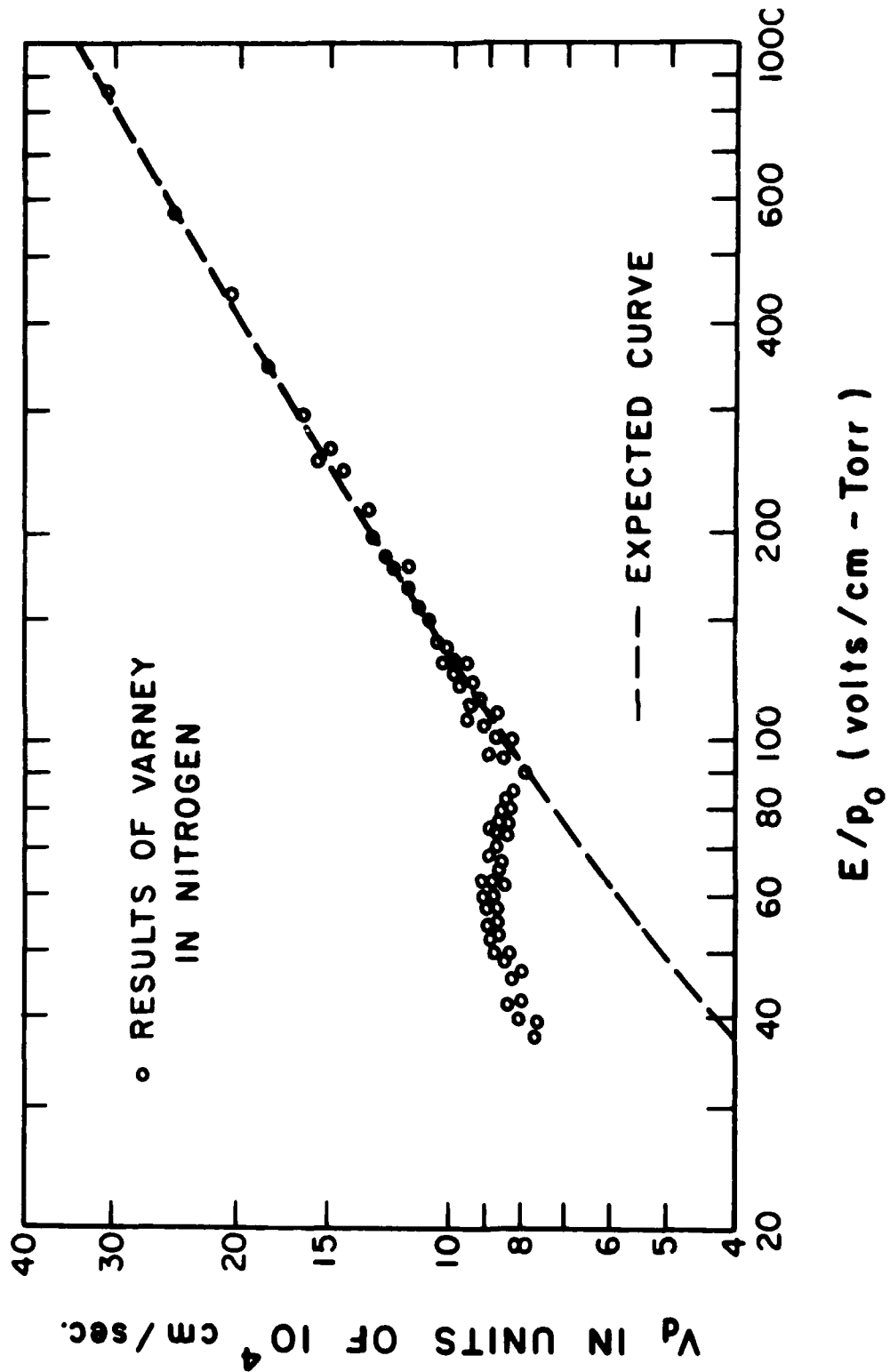


FIGURE 1. RESULTS OF VARNEY IN NITROGEN



would dominate so that the drift velocity measured should be that expected for  $N_2^+$  in  $N_2$ . His apparatus had no mass spectrometer, so he was unable at that time to verify his ion identification hypothesis.

This identification did seem to be supported by the findings of Saporoschenko (1958) who later used a mass spectrometer to study the formation of positive ions in nitrogen. Saporoschenko found that there were, in fact, four positive ions in nitrogen,  $N^+$ ,  $N_2^+$ ,  $N_3^+$ , and  $N_4^+$ .

Woo (1965) did the latest work on nitrogen with a system lacking a mass spectrometer for definite ion identification. Even with exhaustive data analysis, he was unable to distinguish all four ions; his "fast" ion was undoubtedly a composite of  $N^+$  and  $N_3^+$ .

In an effort to understand and explain the complications in molecular gases, several groups have developed mobility devices which incorporate mass spectrometric ion identification. The nitrogen results of one of these groups (Keller, Martin, and McDaniel, 1965) bear careful consideration.

Keller et al. (1965), using a "drift tube-mass spectrometer," found that with some care, and by judicious choice of gas pressure, drift velocity curves for  $N^+$ ,  $N_2^+$ , and  $N_4^+$  in  $N_2$  could be obtained which had the expected shape as  $E/p_0$  was changed. However, there were conditions under which  $N_2^+$  seemed to drift "too fast," and conditions for which  $N_4^+$  seemed to be "too slow." Under no conditions could the  $N_3^+$  data be made to display the expected behavior; in particular, the measured mobility for  $N_3^+$  in  $N_2$  never became constant as  $E/p_0$  was reduced. Consideration of the arrival-time spectra of the ions, however, made it clear that ion-molecule reactions were causing the confusing results.

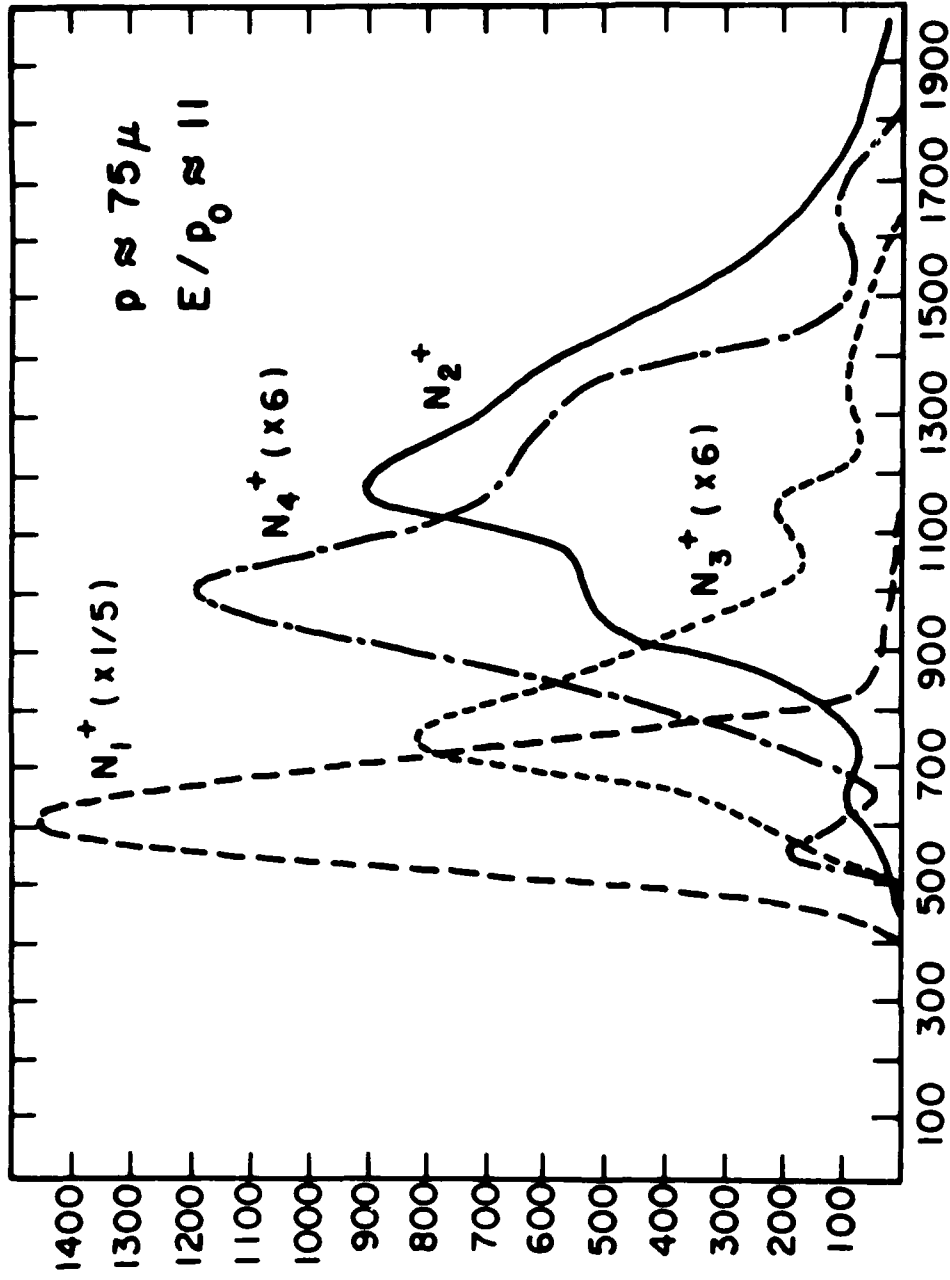
Let us consider the method of operation of the drift tube-mass spectrometer. Ions of the parent gas were formed in a drift tube using a movable electron bombardment ion source and were caused to drift down the tube by a weak axial electric field. A small fraction of the ions which arrived at the end of the drift tube were carried out of a 0.8-mm

diameter pinhole with the sample gas, passed through an essentially field-free differential pumping chamber into a region of low pressure, where they were sorted by a mass spectrometer and counted individually with an ion multiplier. Ions were created in bursts of only 20 microseconds duration and were sorted into one of twenty counters according to their total time of drift. The raw data for this experiment were in the form of histograms; smoothed data for all four ions in nitrogen are shown in Figure 2.

It is important for the interpretation of arrival time spectra from an experiment of this type to understand that the mass spectrometric sorting assures the assignment of a drift time to an ion whose  $m/e$  was known only when it exited the drift tube. Any "history" of ion-molecule reactions undergone in the transit is contained only in the time it took for an ion of the selected  $m/e$  to appear. Thus it is not very surprising, when considering arrival time spectra for reacting ions in a gas, to find large areas of overlap in the peaks. In particular, Figure 2 shows  $N_2^+$  and  $N_4^+$  peaks which appear quite similar. The non-symmetrical shapes of each of these curves strongly suggest that ions of each type spent some of their drift time as the other type. The particular field and pressure conditions in use when the data of Figure 2 were taken were those for which the drift velocity of  $N_4^+$  was slower than expected; one then infers that the ions which emerged as  $N_4^+$  ions had spent a significant fraction of their drift time as  $N_2^+$  ions, so that their total drift time would include time as a slower ( $N_2^+$ ) ion. The ability to unravel completely the information contained in these and similar data would require knowledge of all the reactions and reaction rates for both ions as functions of temperature, pressure, electric field, and excited states.

Conversely, if one reaction taking place in a mobility experiment could be isolated, changes in the peak shapes of the interacting ions could be analyzed to obtain a reaction rate. Just such an analysis has been done by Miller et al. (1967) for ions in hydrogen.

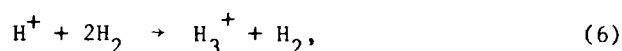
IONS PER CHANNEL PER 40 MINUTES



### DRIFT TIME IN MICROSECONDS

FIGURE 2. ARRIVAL-TIME SPECTRA IN NITROGEN

During a measurement of the drift velocities of the ions in hydrogen using a vastly improved drift tube-mass spectrometer, Albritton et al. (1967) found that while the shape of the  $H^+$  peak in an arrival time spectrum was just what was expected, the  $H_3^+$  peak had a "toe" caused by faster ions. The appropriate arrival time spectra from their investigation are reproduced as Figure 3. Miller et al. (1967) analyzed this toe, and they found that it could be explained by a three-body conversion of  $H^+$  to  $H_3^+$ ,



with a reaction rate constant,  $k = 3.2(\pm 1.0) \times 10^{-29} \text{ cm}^6/\text{sec}$ . Thus, a reaction rate determination could be made by careful analysis of faster ( $H^+$ ) ions which were converted to slower ( $H_3^+$ ) ions in flight.

### III. EVALUATION OF RECENT LABORATORY MEASUREMENTS

First, let us consider the drift velocity measurements in nitrogen. Varney's (1953) results suggested and Woo's (1965) results verified that only a tentative understanding of the complications in nitrogen could be accomplished without mass spectrometric identification of the ions. Even with a mass spectrometer, Keller et al. (1965) were prevented from determining a unique "mobility" for  $N_2^+$ ,  $N_3^+$ , and  $N_4^+$  by the reactions taking place. From study of arrival time spectra, they were able to say that there was strong evidence for a pair of strongly pressure-dependent reactions which interconverted  $N_2^+$  and  $N_4^+$  to the extent that one could never be sure that either of these two ions maintained its identity for the entire drift time. The reactions broadened both peaks, the peak for the faster  $N_4^+$  ions toward late times and the peak for the slower  $N_2^+$  ions toward early times.

Second, consider the measurements in hydrogen. Since there was only one appreciable reaction between  $H^+$  and  $H_3^+$  (see Albritton et al., 1967, for details of others), one could deduce from the broadening of the  $H_3^+$  peak that  $H_3^+$  was the end product of the reaction and could proceed to establish the reaction rate. It should be emphasized that

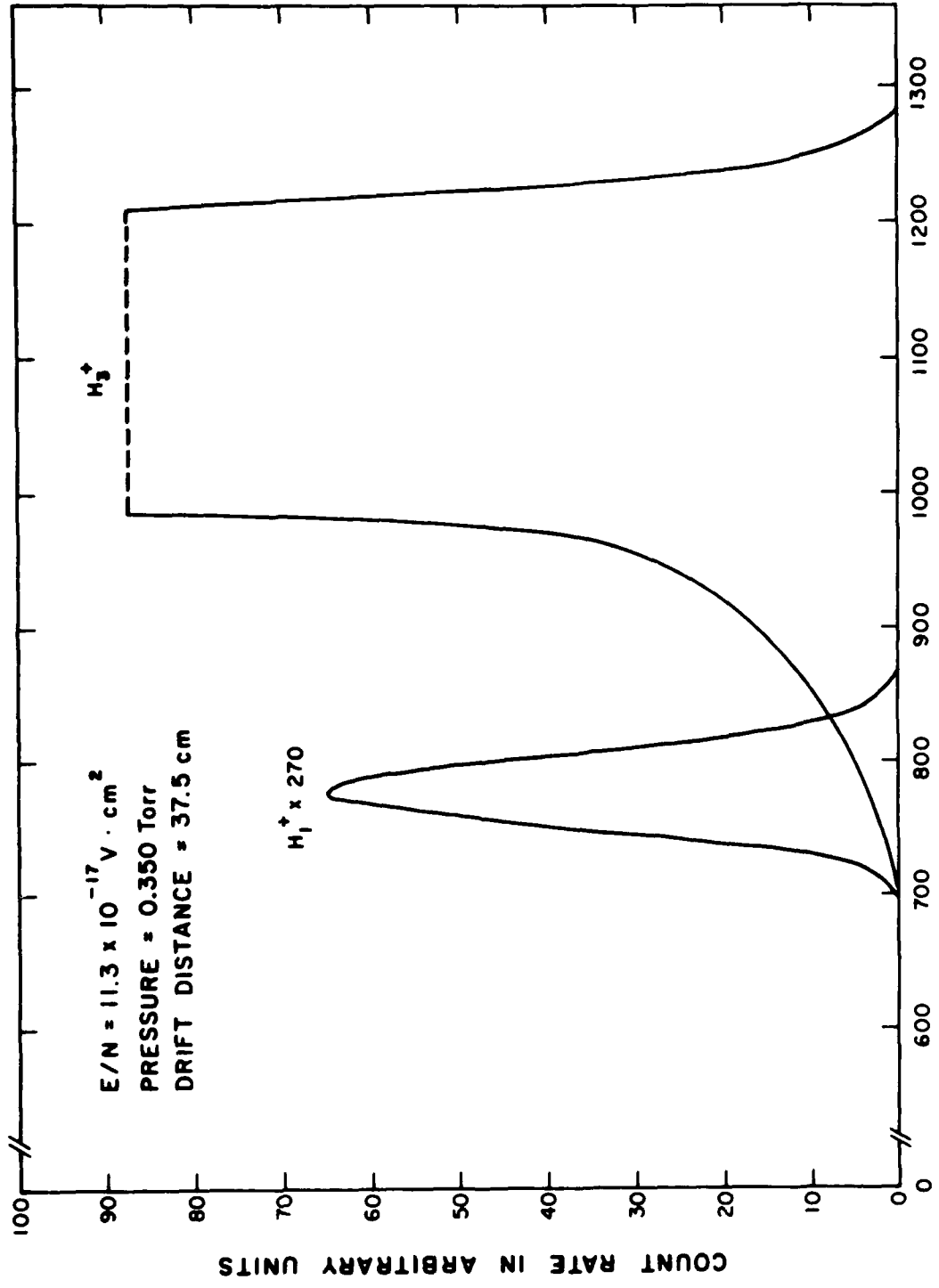
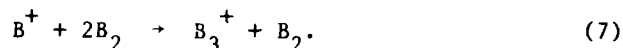


FIGURE 3. ARRIVAL-TIME SPECTRA IN HYDROGEN

without the mass spectrometer the existence of the  $H^+$  could easily have been missed in the presence of the much more intense  $H_3^+$  peak.

Finally, consider what these experiments imply about the expected results of a hypothetical mobility measurement on  $B^+$  ions in  $B_2$  gas. Let us assume that there is a reaction forming  $B_3^+$  ions from  $B^+$ ,



If the reaction rate for (7) is negligible, in the sense that an immeasurably small fraction of the  $B^+$  ions react to form  $B_3^+$  ions under the conditions of the measurement, the only  $B_3^+$  ions which will be seen are those formed by other means. (In hydrogen, for example,  $H_3^+$  is primarily formed from  $H_2^+$  in the source, by the reaction  $H_2^+ + H_2 \rightarrow H_3^+ + H$ . The reaction rate for this reaction is so large that no  $H_2^+$  ions are ever seen with a drift-tube mass spectrometer;  $H_3^+$  ions created thus can be considered to be primary ions.) Under these conditions, the shape of the  $B_3^+$  peak will be predictable, and it will not be smeared toward, or overlap, the  $B^+$  peak.

If the reaction rate for (7) is appreciable, in the sense that many of the  $B^+$  ions react to form  $B_3^+$ , the  $B_3^+$  peak will overlap the  $B^+$  peak, and without the use of a mass spectrometer one could not hope to distinguish between the  $B^+$  ions and the  $B_3^+$  ions formed late in the drift tube.

If the reaction rate for (7) is quite large, in the sense that essentially all the  $B^+$  ions react to form  $B_3^+$  early in the drift tube, the arriving  $B_3^+$  ions cannot be distinguished from  $B_3^+$  otherwise formed in the source, and there is no evidence that  $B^+$  ions had ever existed!

Thus we see that the presence of a nonnegligible reaction in a mobility measurement will cause the arrival time peak of the product ion to be smeared and to overlap that of the reacting ion to the extent that information about the initial concentration of the reacting ion is lost. If there is more than one reaction taking place, the product ion's arrival time spectrum will be complicated by each and every ion from which it is formed during the drift field transit.

#### IV. EFFECT OF LABORATORY FINDINGS ON IN SITU MEASUREMENTS

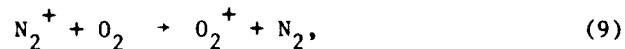
Let us now consider what effect these laboratory findings will have on measurements in the lower ionosphere which employ ionic mobilities. Since the lower ionosphere is characterized not only by large numbers of ions, electrons, and neutral particles but also by numerous reactions, an effort should be made to evaluate the effect of these reactions on any proposed measurements.

The most intriguing recent suggestion is the use of ionic mobility measurements for number density determinations of individual ionic species. We have seen that reactions could affect the collected currents due to both the number densities of the reacting ions and the number densities of the product ions. The magnitude of the effect of a particular reaction can be most easily measured by comparing the appropriate reaction rate with the collision rate. Gioumouzis and Stevenson (1958) give the (ion-molecule) collision rate constant as

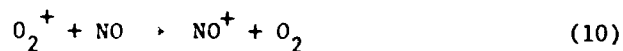
$$k_c = 2\pi e(\alpha/\mu)^{1/2}, \quad (8)$$

where  $e$  is the electronic charge,  $\alpha$  is the polarizability of the gas, and  $\mu$  is the reduced mass of the colliding particles (for a recent discussion, see Fehsenfeld et al., 1967). This rate constant applies to spiraling or orbiting collisions between thermal energy ions and molecules.

Let us consider two typical atmospheric reactions for which the reaction rates have been measured. The first is



for which the reaction rate has been measured to be  $k = 1.0 (\pm 0.5) \times 10^{-10} \text{ cm}^3/\text{sec}$  (Ferguson, 1967). For this collision,  $k_c = 5.5 \times 10^{-10} \text{ cm}^3/\text{sec}$ . Thus we see that an original number density of  $\text{N}_2^+$  ions will be diminished to less than  $1/e$  of its original value after the  $\text{N}_2^+$  ions have had an average of six collisions with  $\text{O}_2$  molecules. The second reaction to be considered is



for which the reaction rate constant has been measured to be  $k = 8 (+2, -5) \times 10^{-10} \text{ cm}^3/\text{sec}$  (Goldan, et al., 1966). For this collision,  $k_c = 5.6 \times 10^{-10} \text{ cm}^3/\text{sec}$ . Thus we see that essentially every such collision results in a charge transfer! It is not the case that these reactions have unusually fast reaction rates; rather, a reaction rate constant of about  $10^{-10} \text{ cm}^3/\text{sec}$  is what one expects for exothermic charge transfer reactions (Ferguson, 1967).

Therefore, while under the influence of the electric field used for a mobility measurement, the ions and neutrals will be changing their identities rapidly due to the collisions imperative for such a measurement. If the electric field is assumed to be weak, it is true that the number density of each ion and each neutral will in general be exactly the same at the collector as it was before the measurement (in the "free stream"). However, the particles will have lost their identities; the appropriate reaction rates are such that many identity changes may take place in a short spatial distance. Thus the drift time associated with each ion arriving at the collector is not a unique identifier of the ion type which existed just before entry into the electric field nor of the ion type which was collected.

While reactions involving positive ions have been used as examples in the above discussion, the same argument should hold for negative ions. However, there have been considerably fewer measurements of negative ion reaction rate constants, so that one cannot as yet be absolutely sure that there will be enough reactive collisions between negative ions and neutrals to invalidate mobility measurements in the lower ionosphere.

We can conclude that mobility spectra for a reacting ion-neutral mixture, of which the atmosphere is one of the worst examples, will be unable to yield any information about individual positive ion number densities. Each spectrum can be expected to have the shape of a "humpy continuum" centered on an average ionic mobility in air.

Thus it is seen that the use of a mobility technique necessitates collisions. In a reacting gas, such as our ionosphere, these collisions



lead to reactions which negate the mobility results. Hoping to save the idea of the experiment, one might suggest elimination of the collisions to stop the reactions. This would only be possible at high altitudes, however, and would lead to a form of time-of-flight mass spectrometry, which is far from a mobility measurement.

It has also been suggested that ionic mobilities could be used in conductivity and/or total ion density measurements in the lower ionosphere. Here the reactions will not change the total ion number density, but they will require that one use a carefully selected average mobility for ions in air. Thus, with an appreciation for the limited accuracy necessarily associated with the use of an average mobility value, ionic mobilities could be used for measurements of conductivity and/or total ion number densities.

If one assumes that typical atmospheric ions have a mass of about 30 amu, consideration of published mobility data for nitrogen (Keller et al., 1965; Woo, 1965), oxygen and carbon monoxide (Varney, 1953), argon (McAfee et al., 1967), and air (Sinnott, et al., 1967) leads one to estimate an average mobility for positive ions in air of  $2.4 \pm 1.2$  cm<sup>3</sup>/V-sec.

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