Collection of Ions Produced by Alpha Particles in Air

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In the measurement of the ionization caused by alpha particles in air, recombination effects between slowly moving positive and negative ions (the latter formed by electron attachment to oxygen) have to be considered. The usual procedure in such measurements is to determine the saturation current (by extrapolation of reciprocal current versus reciprocal voltage curves to infinite field strength) according to the Jaffé theory. A paper by Wingate, Gross, and Failla has cast doubt on the validity of this extrapolation technique, in that the authors propose a field-independent part of the recombination amounting to 3.3% at atmospheric pressure in air. This proposal implied that all previous measurements of W_α for air were in error by this amount and that this error is a possible cause for the reported difference (3–4%) between W values for alpha and beta particles in air. In view of our own W measurements we felt compelled to re-examine this supposedly field-independent part of the recombination. Approximating the experimental conditions of Wingate, Gross, and Failla we have not been able to reproduce their effect and our experiments demonstrate the validity of the usual extrapolation techniques.

INTRODUCTION

An investigation of the effects of pressure and collection potential on the collection of ions produced by alpha particles in air was published by Wingate, Gross, and Failla.[1] Their experiments, conducted at pressures between 4 cm of mercury and one atmosphere, showed that at every pressure a plateau in the current-voltage curve could be obtained and that the value of the plateau current increased as the pressure decreased until at 10 cm of mercury a maximum ionization current was observed which was independent of further reduction in pressure. The ionization current at atmospheric pressure, though independent of the collecting potential over a large range of voltages, was 3.3% lower than the value at 10 cm.

It has previously been generally accepted that if a significant amount of recombination occurred, there would be no plateau in the current vs voltage curve and the saturation current might be determined by an extrapolation method based on the theory of Jaffé.[2,3] Therefore, Wingate, Gross, and Failla conclude that for the ionization by alphas in air the usual extrapolation procedures are inadequate and a field independent (but pressure dependent) part of the recombination has also to be taken into account. This would cast serious doubt on all previous determinations of W (the average energy expended in producing an ion pair) for alpha particles in air. Therefore, Wingate, Gross, and Failla suggest that this previously undetected part of the recombination is a possible cause for the "apparent" increase of W_α in air as the alpha energy decreases as well as for the reported difference (3–4%) between W values for alpha and beta particles in air.

Recently we conducted experiments aiming at a redetermination of the important value of W_α in air (the results of this work will be published elsewhere),[4] and since this field-independent part of the recombination would seriously affect the final interpretation of our measurements, we felt compelled to re-examine this effect. The method used was the same as applied by Wingate, Gross, and Failla; extrapolated saturation currents were compared at different pressures.

EXPERIMENTAL

The equipment used, which was also used for the absolute measurement of W_α, consisted of two identical cylindrical (diameter 45 cm, height 60 cm) chambers which could be evacuated or pressurized. The Po^{210} alpha source was either deposited on a flat electrode (to obtain nearly uniform field as in our absolute W measurements) or (for the repetition of the geometry used by Wingate, Gross, and Failla) as a spot on a rod of 8-mm diameter. With each type of electrode both the full Po^{210} alpha energy (5.3 Mev, reduced only slightly by source self-absorption) was used (as a checking experiment for the absolute W_α measurements) and a reduced alpha energy by putting an absorber on the source such that the residual energy was 0–2 Mev (for dense ionization and larger probability of field independent recombination) as in the Wingate, Gross, and Failla experiments. For the measurement of ion currents, vibrating reed electrometers were used. When measuring small currents, one of the twin chambers is used for the simultaneous measurement of the background. The highest collecting potential used was 40 kv, giving field strengths of the order of 2 kv/cm and higher.

First, the situation most nearly approximating the W_α measurements was tried. In this case, the Po^{210} was deposited on the flat electrode, no absorber was used and the intensity of the source was $\sim 10^3$ disintegrations per second, giving on the average one alpha track present in a time interval for complete ion collection (approxi-

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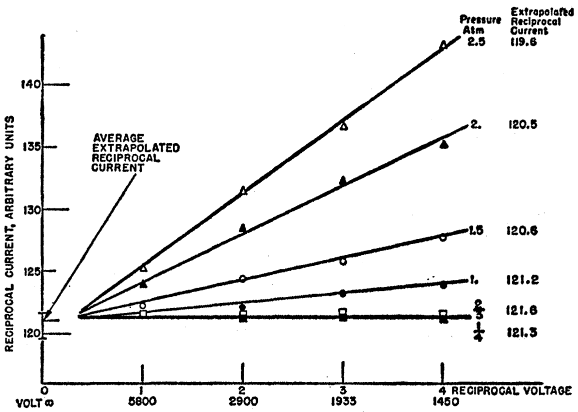

FIG. 1. Chamber saturation curves at different pressures. Within experimental error the currents extrapolated to infinite field strength are independent of pressure.

mately a millisecond). The results are summarized in Fig. 1 where a family of extrapolation curves, taken in the pressure range from 0.25 to 2.0 atm of air, is shown. The frame used is reciprocal current vs reciprocal voltage, since it is well known that the Jaffé theory, even if applied to widely varying conditions, leads to straight lines in this frame of reference when saturation is nearly attained.[5] The curves of Fig. 1 are nearly straight lines and give within the uncertainty of the measurements of about 0.3% the same current when extrapolated to infinite field strength.

This lack of a pressure dependence of the extrapolated current in our experiment is corroborated by the measurements of Biber, Huber, and Mueller[6] who obtained in air between 4 and 6 atm curves very similar to those of Fig. 1. Our results in no way contradict those of Kimura *et al.*[7] or those of Alder, Huber, and Metzger,[8] who, while they do not challenge the validity of the usual extrapolation methods, state that very large collecting fields are necessary to prevent significant recombination of ions in air.

From this, we can conclude that for our own absolute W_α measurements where we have a fairly uniform high collecting field at atmospheric pressure and a low-intensity source, the usual extrapolation procedures can be accepted with confidence.

However, for the purposes of further intended ionization measurements, dealing with higher intensity sources or lower energy alphas, we felt it was necessary to try to reproduce the measurements of Wingate, Gross, and Failla in our own system. This was accomplished in the following steps:

(1) To obtain high ionization densities, a high intensity Po^{210} source (10^7 disintegrations per second) was deposited on the flat electrode.

(2) A source similar to that in (1) was covered with a Mylar film of approximately 3 mg/cm^2 thickness such that the residual energy of the alpha particles was 0–2 Mev, as in the experiments of Wingate, Gross, and Failla.

(3) A source again of approximately the same intensity as in (1) was deposited as a spot on a brass cylinder of 8-mm diameter and the residual energy of the alphas was reduced to 0–2.5 Mev by vacuum evaporation of gold on the cylinder.

The measurements in all these three cases in air resulted in curves similar to those in Fig. 1 showing no detectable dependence of the extrapolated saturation current on pressure.

It is interesting to note that, in order to detect any possible systematic error in the source preparations or in the electrode arrangements, the experiments have been repeated in a nitrogen atmosphere where recombination effects are on a smaller scale and where a pressure dependence of the saturation current is not expected. These checking experiments turned out to be very useful. In one case, when a source deposited on the brass cylinder was covered with the Mylar film, an approximately 1% decrease in the extrapolated current was observed *both in air and in nitrogen* as the pressure was increased from a low ($\sim\frac{1}{5}$ atm) value to 1 atm. Careful investigation showed that the Mylar fitted loosely around the cylinder. Since a gap as small as 0.1 mm can explain the 1% effect simply by the change in the residual energy of the alpha particles when the gap is filled with air or nitrogen of varying pressure, the use of Mylar as an absorber, as applied in the experiments of Wingate, Gross, and Failla, was discontinued in favor of the vacuum-evaporated gold as described in (3). (It is also possible for a plastic coat obtained from dipping the rod into a solution to separate slightly from the rod upon drying.)

DISCUSSION

Our experiments do not show plateaus in the current-voltage curves and the extrapolated saturation currents appear to be independent of pressure. Consequently, under the conditions checked there seems to be no necessity for assuming a field independent part of the recombination and the usual extrapolation methods appear to be adequate in the investigation of the ionization caused by alpha particles in air. Our absolute measurements, as reported in reference 4, resulted in $W_\alpha = 35.14 \pm 0.1$ ev/ion pair which is definitely larger than $W_\beta = 33.7 \pm 0.3$ ev/ion pair.[9] We consider the difference between them to be a real effect having its explanation in the energy dependence of W_α in air.[10]

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Wingate, Gross, and Failla suggest that this energy dependence may be only an apparent one in air due to difficulties of ion collection. However, the electronegative behavior of a gas (responsible for large recombination losses) and the dependence of W_α on energy were found to be uncorrelated effects. A good example is nitrogen, the major component of air, for which an energy dependence was found by Jesse and Sadauskis.[11] On the other hand, nitrogen is nonelectronegative and permits an easy determination of saturation currents at relatively low-field strengths. Therefore, the observed energy dependence has to be considered real in nitrogen and can be accepted for air.

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Upper Bound on Total Electron Scattering Cross Sections in Hydrogen*

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Dispersion relations for electron-hydrogen scattering are combined with existing scattering length calculations. The sign of the scattering length is shown to give an upper bound on $\int\sigma(k)dk$ where $\sigma(k)$ is the total cross section for scattering of electrons of incoming momentum $\hbar k$. Recent calculations of the scattering length are used to determine this limit. An experiment by Fite *et al.* satisfies this bound, agreeing with the recent calculations of the scattering length.

IN a recent paper[1] dispersion relations were applied to low-energy electron scattering by hydrogen atoms. The results of that work indicate a connection between angular distributions at a particular energy and total cross sections at all energies. In the present work knowledge of the scattering lengths is combined with the dispersion relations for rearrangement collisions to give a bound on the total cross section integrated over all energies. The arguments will be made for electron-hydrogen scattering; their extension to other systems will be obvious.

The appropriate dispersion relations for electron-hydrogen scattering at zero incoming electron energy are[1]

$$\mathrm{Re}(f-\tfrac{1}{2}g)=(f-\tfrac{1}{2}g)_{\mathrm{Born}}+\frac{1}{2\pi^2}\int_0^\infty \sigma_t(k)dk-\tfrac{1}{2}R, \quad (1)$$

where f and g are the zero-energy scattering amplitudes for direct and exchange electron scattering at angle $\theta=0$, σ_t is the total cross section for scattering of electrons of incoming momentum $\hbar k$, R is a positive number[1] which depends on the bound-state wave functions of the e-H system, and $(f-\frac{1}{2}g)_{\mathrm{Born}}$ is the first Born approximation to the forward amplitudes f and g.

At zero incoming electron energy we can express the singlet $(f+g)$ and triplet $(f-g)$ s-wave phase shifts $\delta_0{}^{\pm}$ in terms of a parameter $a_\pm$, the scattering length, by[2,3]

$$k\cot\delta_\pm=-1/a_\pm+\cdots. \quad (2)$$

Comparison of (2) with the partial wave expansion of the amplitudes[4] $(f\pm g)$ yields the elementary result (at $k=0$)

$$\mathrm{Re}(f\pm g)=-a_\pm \quad\text{and}\quad -\mathrm{Re}(f-\tfrac{1}{2}g)=\tfrac{3}{4}a_-+\tfrac{1}{4}a_+. \quad (3)$$

In the case of electron-hydrogen scattering $(f-\frac{1}{2}g)_{\mathrm{Born}}$ at zero energy equals $-2a_0$, where a_0 is the Bohr radius.[5] Thus,

$$\mathrm{Re}(f-\tfrac{1}{2}g)=-\tfrac{3}{4}a_--\tfrac{1}{4}a_+=-(\tfrac{1}{2}R+2a_0)+\frac{1}{2\pi^2}\int_0^\infty \sigma_t dk. \quad (4)$$

Now the scattering length is a zero-energy property of the system and has been calculated by a variety of researchers for e-H scattering.[3,6,7,8] While the numerical values of their results are not in complete agreement, they all predict that the singlet and triplet scattering lengths are both positive. It is well known that the scattering length is negative for a system with no bound states, and becomes positive for a system with a bound state near zero energy. The most recent calculations indicate $a_-\sim 1.9a_0$ (triplet),[6] $a_+\sim 6.2a_0$(singlet).[6,8] Some of these results[6] are based on elegant variational calculations, and are expected to be quite reliable. The singlet length might be expected to be positive because binding energy calculations and observations indicate the existance of one bound state near zero energy. A virtual s state within one ev of zero energy could change

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