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MEASUREMENT OF PRIMARY SPECIFIC IONIZATION IN NOBLE GASES

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Possible methods are discussed for measurement of the primary specific ionization produced by charged particles in a gas. It is shown that in measurement of the primary ionization in noble gases the result is as a rule exaggerated. On the basis of an analysis of the causes leading to the increase of the experimental data in comparison with theory, it is shown that the value closest to the primary ionization is obtained in measurements with a streamer chamber. The validity of the conclusions enumerated is illustrated for the case of primary ionization measurement in helium.

INTRODUCTION

MEASUREMENTS and theoretical calculations of the specific primary ionization produced by a charged particle in a gas have been made by a number of workers[1-10] over a wide range of ionizing particle energy. Interest in the primary ionization is due to the fact that in many fields of experimental physics involving the ionization of gases, a knowledge of accurate values of primary ionization is extraordinarily important.

The following methods exist for measurement of primary ionization:

1. Measurement of the efficiency of a Geiger counter.[1-4] In this case the primary ionization is determined from the relation

$$S = -\frac{\ln(1-\varepsilon)T}{273LP},$$

where S is the primary specific ionization at a gas temperature of 0°C and pressure 760 mm Hg, T is the gas temperature in degrees Kelvin, L is the path length of the particle in the counter, and P is the gas pressure in atmospheres.

2. Counting the number of drops in a particle track in a cloud chamber.[5,7] Here it is necessary that the particle pass through the chamber during the sensitive time.

3. Counting the number of streamers in the track of a particle in a streamer chamber.[8] Here the following conditions must be satisfied: a) The radius of the photographic image of the streamer R must be much greater than the distance of diffusion of the electrons L during the delay time between the passage of the particle and the application of the high-voltage pulse; if this condition is satisfied, the secondary ionization electrons are not recorded in the form of individual streamers;[8] b) the sensitivity of the photographic recording must be sufficient to record all streamers, independent of their fluctuations in brightness.

It should be noted that all of the methods enumerated contain sources of errors which can strongly distort the experimental data on primary ionization. These sources are the processes in the gas occurring in the time between the passage of the particle and the moment of recording.

In the case of the noble gases these processes are as follows:

1. Ionization of impurity atoms in collisions with excited atoms of the main gas:

$$X^* + Y \rightarrow X + Y^+ + e.$$

The cross section for this reaction is 10^{-15}–10^{-16} cm²;[11] here an amount of impurity of the order of tenths of mm Hg is sufficient that in a time of $\sim 10^{-6}$ sec all excited atoms (or molecules) of the noble gas which are capable of ionizing the impurity have produced ionization (this effect is particularly important in a cloud chamber, since impurities such as water vapor and alcohol are unavoidably present in the working volume of the chamber). The error in determination of the primary ionization can reach tens of per cent.

2. Knockout of electrons from the walls of the device by photons arising from radiation of excited noble

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gas molecules (this effect is important for Geiger counters).

In the radiative de-excitation of excited atoms, a resonance–radiation capture effect is observed, as the result of which diffusion of resonance radiation occurs. Removal of electrons from the counter walls as the result of diffusion of radiation to the walls in a time of the order of the resolving time of the coincidence circuit is unlikely. (In 1 μsec the radiation diffuses a distance of the order of 1 mm.[12]).

However, in a noble gas the formation of an excited molecule in a collision of an excited atom with two neutral atoms occurs with a high probability,

$$X^* + 2X \rightarrow X_2^* + X.$$

The rate coefficients of this reaction in He, Ne, Ar, and Kr at a temperature of 300°K are respectively[13] 2.5×10^{-34}, 5×10^{-34}, 9.8×10^{-33}, and 4×10^{-32} cm^6/sec.

The excited molecules in their de-excitation emit photons (with energies of 8–18 eV) capable of knocking electrons out of the counter wall. The contribution to the measured ionization from this process in the case of He and Ne under ordinary conditions is insignificant ($\sim$ 1%), but if a counter is filled with argon or krypton to a pressure of tenths of an atmosphere, we can obtain an increase in the measured ionization of several per cent in a Geiger–Müller counter.

3. Photoionization of an impurity in the process of resonance radiation diffusion. This process plays a considerably smaller role than process 1 in view of the small cross section for photoionization.[14]

4. Formation of a molecular ion in a collision of an excited atom with a neutral atom

$$X^* + X \rightarrow X_2^+ + e.$$

Only levels with an excitation energy V greater than the potential necessary for molecular ion formation contribute to this reaction (in the case of helium, for example, $V_{\mathrm{He}_2} = 23.4$ eV[15]). The cross section for molecular ion formation is $\sim 10^{-15}$ cm^2,[16] and the contribution of this process to the primary ionization measurement in the case of helium can be of the order of several per cent.

5. Attachment of electrons to impurity atoms (water vapor, alcohol, and so forth[8, 11]). This effect is important in self-quenching Geiger counters and in the streamer chamber.

Thus, all experiments on measurement of primary ionization in which the above effects have not been taken into account must give distorted results (usually exaggerated) in comparison with theoretical calculations (see Table I).

Primary ionization measurements in a streamer chamber filled with a noble gas can be free of the above deficiencies to a considerable degree. In fact, in contrast to the cloud chamber and Geiger counter, the streamer chamber can always be filled with a pure noble gas. Consequently, all effects associated with the presence of an impurity are excluded. In addition, in contrast to Geiger counters, in a streamer chamber filled with a pure noble gas the effects of electron knockout from the walls do not play a role.

Thus, in a streamer chamber when the conditions stated above are satisfied a value closer to the primary ionization can be obtained, which is insignificantly greater than the number of primary ionization collisions (as the result of process 4).

EXPERIMENTAL RESULTS AND COMPARISON WITH THEORY

The considerations which we have discussed are valid for any noble gas. We will demonstrate this in the case of measurements of the number of primary ionizing collisions in helium.

Table I lists the results of calculations and of experimental studies of primary ionization in helium by various methods.

Table I.

Source of data and method of measurement	Ionizing particles	Specific primary ionization at a pressure of 1 atm and t = 20°C (cm^{-1})
[7], cloud chamber	Electrons with momentum p = (0.71 – 9) × 10^6 eV/sec	6.6
[4], Geiger counter	Cosmic-ray particles	5.96
[1], Geiger counter	Electrons with minimum ionization I_{min}	4.67 ± 0.06
Our data, streamer chamber	Electrons with I_{min}	3.57 ± 0.1
[10], theory	Electrons with I_{min}	3.25
[9], theory	Electrons with I_{min}	3.37

As an illustration of the effect of an impurity in the gas on the results of a primary ionization measurement, we have listed in Table II the number of "primary" ionization collisions per cm. of path of a particle with minimum ionization, measured in a streamer chamber filled with pure helium (impurity concentration $< 10^{-3}$%) and with helium with impurities of nitrogen ($\sim$1 Torr) and xenon ($\sim$ 0.2 Torr). From the results, which are listed in Table II, it is evident that a small amount of nitrogen and xenon impurity provides a substantial increase in the number of measured "primary" ionizing collisions.

Table II.

Filling	Primary specific ionization at a pressure of 1 atm and t = 20°C (cm^{-1})
He	3.57 ± 0.1
He + 1 mm Hg N_2	4.23 ± 0.1
He + ~ 1 mm Hg N_2 + ~0.2 mm Hg Xe	4.74 ± 0,15

Since the concentrations of N_2 and Xe are very small, the effect of direct ionization of the impurity in primary collisions can be neglected and the observed increase in the "primary" collisions can be explained solely by impurity ionization occurring mainly in the processes

$$\mathrm{He}^* + \mathrm{N}_2 \rightarrow \mathrm{N}_2^+ + \mathrm{He} + e,$$
$$\mathrm{He}^* + \mathrm{Xe} \rightarrow \mathrm{Xe}^+ + \mathrm{He} + e,$$

which have respective cross sections of 7×10^{-16} and 1.3×10^{-15} cm^2.[11]

The primary ionization measurements in a streamer chamber filled with helium, which are listed in the tables, were obtained by us with consideration of the requirements enumerated above on the chamber operating conditions and the photography. Fulfillment of these requirements was assured by the following measures:

1. Purity of the gas in the measurements with pure helium was assured by constant circulation of the helium through a region filled with calcium heated to 500° C and a trap cooled to liquid nitrogen temperature.

2. The condition $L \ll R$, as we have shown in [8], in a chamber filled with helium or helium with an impurity is easily satisfied under our conditions where the delay time is 200 ± 20 nsec.

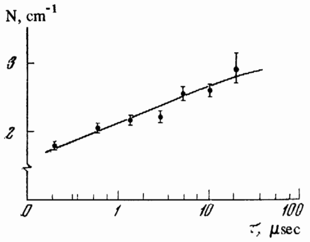
3. Increase of the photographic detection sensitivity as the result of using a three-stage image converter tube permits working in a region of streamer length at which there is no electrical interaction between the streamers and without losing a fraction of the streamers because of brightness fluctuations. The track photographs were analyzed by the method of counting "empty" intervals in a given length along the track[17] (i.e., intervals not containing streamer centers). The probability of having such an interval (of length l) is related to the number of primary ionizing collisions per unit track length (n) by the equation $w = \exp(-nl)$.

This method can be used to determine the number of primary ionizing collisions in a track in spite of the diffusion of electrons (the condition $L \ll R$ must, however, be satisfied). In fact, the displacement of the streamer centers along the track as the result of electron diffusion has a random nature and does not change the distribution of interval lengths; the displacement of the centers across the track does not change the interval lengths along the track.

The method of counting "empty" intervals cannot be used to determine primary ionization in the case when the condition $L \ll R$ is not satisfied (large delays of the high-voltage pulse). In this case the primary ionization can be determined (with a poorer degree of accuracy than in the method described above) from comparison of the measured number of streamers in the track with the calculated number. The calculation must include: 1) overlap of the photographic images of the streamers as the result of electron diffusion in the track; 2) the total number of ion pairs (total ionization); 3) the expected value of primary ionization.

Calculations of this type have been made by us with a computer for a primary ionization value of 3.25 cm^{-1}.[10] In the figure the calculated curve is compared with the measured number of streamers in a particle track in a chamber filled with helium and to a pressure of 0.6 atm. From comparison of the data presented in Tables I and II and the figure, the following conclusions are evident.

1. Primary ionization values in helium measured in a cloud chamber, a streamer chamber, or with Geiger counters exceed the theoretically predicted values. The causes of this, as previously noted, are ionization of an impurity, knockout of electrons from the walls on de-excitation of excited molecules, and the process of molecular ion formation in the noble gas.



Number of streamers N in 1 cm of track as a function of delay time τ in application of the high-voltage pulse. The chamber was filled with helium to a pressure of 0.6 atm. The smooth curve is the result of theoretical calculation.

2. The least deviation from theory is obtained with the data from the streamer chamber, since in this case a large part of the effects which introduce systematic errors into the measurements are excluded. The excess of the experimental results over the theoretical values in this case can be used to estimate the contribution to the ionization from the process of molecular ion formation.

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