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Gas phenomena in spark chambers*

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The spark chamber is used to study the following gas phenomena: drift of single electrons under the influence of an electric field, deexcitation of metastable rare-gas atoms in collisions with molecules, and ionization by high-energy particles of various energies. The method determines the average number of electrons from the spark efficiency and is capable of showing that a large fraction of the primary ionization is due to metastable atoms.

I. INTRODUCTION

A spark chamber is an instrument used in particle physics to determine the trajectories of charged particles by detecting the track of ionization produced in a gaseous medium. It consists of two (plane) electrodes between which a high-voltage pulse causes sparks along the tracks. In an effort to understand the conditions of spark-chamber operation in this context, we have studied how the probability of spark formation after the passage of a particle ("efficiency") varies with gas composition, dc field strength ("clearing field"), and high-voltage pulse delay.

One main result is that the retarded ionization via metastable atoms (Penning ionization) gives an important contribution to the total ionization caused by the high-energy particle. We show in Secs. VII and VIII how it was isolated and how it is influenced by the contamination of molecular gases.

Another aspect of this work is that our method, which is very simple, can be used to study gas phenomena in their own right. The technique yields accurate measurements of electron drift velocity and primary ionization (presented in Secs. V and VI), and presumably could be used to study electron diffusion and attachment, which we have not investigated. The emphasis is mostly on the method rather than on the discussion of measurement errors.

II. COMPONENTS OF IONIZATION

In order to arrive at a classification of the free electrons which are present in the gas after the high-energy particle passed, we make the following distinctions.

(i) The ionization process is called "instantaneous" if caused by a charged particle in a collision with a molecule.

(ii) The ionization process is called "retarded" if caused by the deexcitation of a metastable rare-gas atom in a collision with a molecule of low ionization potential (Penning ionization).

(iii) Instantaneously produced electrons may be "primary" if they result directly from ionizing collisions of the traversing particle with gas molecules or they may be "secondary" if they result from ionizing collisions of primary or secondary electrons with gas molecules. Retarded ionization may, in principle, be "primary" as well, if the metastable state was excited directly by the traversing particle, or it may be "secondary," if the metastable state was excited in collisions with primary or secondary electrons with rare-gas atoms.

We also distinguish between free electrons that result from collision processes in the gas alone and free electrons that involve collision processes in the foils of the spark chamber.

After the passage of the high-energy particle an average number of free electrons of each category will be present in the gas. These numbers are denoted in Table I.

The number of primary retarded electrons produced in the gas (A_p^g) is expected to be very small because of the smallness of the electron magnetic moment. Also there is no Penning ionization in the foils.

As the range of instantaneously produced primary electrons is limited to typically 0.1 mm (in 97% of the cases at 1 atm), the secondaries and the metastable atoms originating from it form small clusters around their parent primary electron.

We will show in the following sections how some of the above categories of free electrons have been isolated from each other using a spark chamber.

III. STATISTICAL METHOD TO DETERMINE THE MEAN NUMBER OF FREE ELECTRONS

Following the picture of spark formation as given by Meek[1] and Raether[2] a spark will always develop in a gaseous medium under the influence of a sufficiently high electric field if there is a free electron in the sensitive region to start the avalanche. For a given field, the avalanche needs a certain length d to make a spark, and if the distance between the electrodes is b, the length of the sensitive region is given by $b-d$. In the following we are not concerned with the details of spark formation, but the spark is only used as an indicator for the presence of at least one electron in the sensitive region at the time when the high-voltage pulse is applied to the electrodes.

At some time after the passage of a high-energy particle across the electrodes, a number of free electrons are present in the sensitive region. This number is statistically distributed around a mean value which gives rise to a finite probability P_0 that there will be zero electrons in the sensitive region. If there are not too many electrons (say between 0 and 10) this probability can be measured because it is equal to the frequency with which the chamber does not spark under otherwise identical circumstances. The inefficiency of the spark chamber measures P_0 and hence, if one knows the form of the probability distribution, it also measures the mean number of electrons in the sensitive region at the time of the high-voltage pulse.

Since the primary electrons are created independently, their number follows a Poisson distribution. Secondary electrons, on the other hand, do not contribute to the probability of spark formation because they cluster with their primaries. The metastable atoms can be separated from the free electrons by a dc field between the electrodes which removes the free electrons (see Sec. VII below). The electrons from separated metastables are again produced independently and, therefore, also satisfy a Poisson distribution. Finally, electrons from unseparated metastables behave like secondaries and do not contribute to the probability of spark formation.

After this discussion it is clear that the statistical law for the number of electrons under the specified circumstances is the Poisson distribution

$$P_K^X = \frac{e^{-X} X^K}{K!},$$

where X is the mean and K is the actual number of electrons;

$$P_0^X = e^{-X}$$

is the well-known special case for the probability to find zero electrons. In our method, it is set equal to the measured inefficiency of the chamber which, therefore, determines the mean number of electrons, provided the metastable atoms are either completely unseparated or completely separated from their primary electrons.

The method used in Secs. V–VIII relies on the determination of the number of independently produced electrons in the sensitive region of a spark chamber as a function of the measuring conditions.

IV. APPARATUS

The spark chamber used consisted of two aluminium foils, 10 mm apart, spanned over insolated support frames. (This was actually one module of a larger set of old optical spark chambers constructed five years ago for a high-energy experiment, i.e., not optimized for the present purpose.) Enclosed in a vacuum tank and sandwiched between two horizontal scintillation counters, the chamber was triggered by a cosmic-ray particle which had struck both counters in coincidence, and had hence traversed the chamber. The flux of cosmic rays was around 25/sec. A lumped delay line delivered a more or less rectangular pulse through a spark gap acting as a switch into the chamber. A constant dc field could be applied to the electrodes. Furthermore, we set a dead time of ~0.5 sec after each sparking, during which any coincidence was ignored; this prevented ions of previous discharges from causing new sparks. The necessary dead time was determined by refiring the chamber a definite time after sparking and thus measuring the effective number of residual electrons as a function of time. The gas composition was controlled with a mass spectrometer. A schematic diagram of the apparatus is presented in Fig. 1, and Table II gives some relevant dimensions.

Scaler 1 counted the number of coincidences

TABLE I. Notation for average numbers of various types of free electrons present in the gas.

Type of electron	From collisions in gas alone	Involving collisions in foils
Primary instantaneous	N_p^g	N_p^f
Secondary instantaneous	N_s^g	N_s^f
Primary retarded	A_p^g	···
Secondary retarded	A_s^g	A_s^f

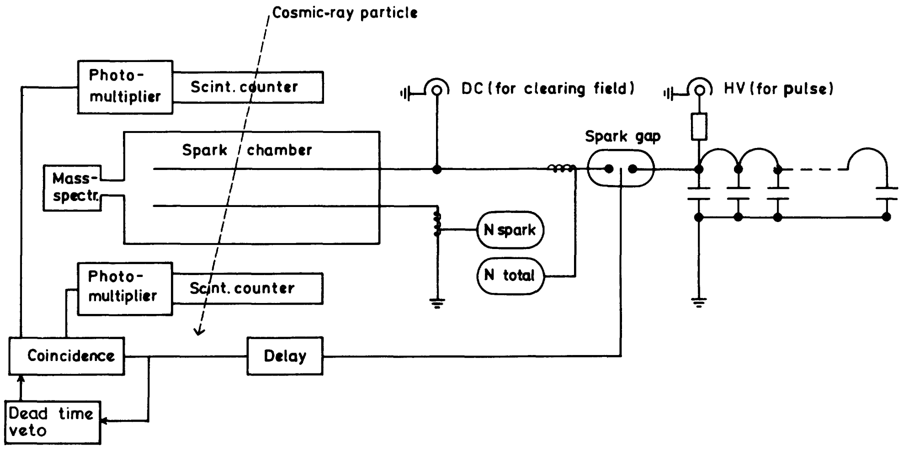

FIG. 1. Schematic diagram of the apparatus used.

(N_{tot}), and scaler 2 the number of times (N_{spk}) the chamber fired. In each run the *average* number of electrons (X) that independently caused a spark was given by the two scaler readings as the logarithm

$$X = -\ln(1 - N_{spk}/N_{tot}),$$

with error

$$\Delta X = \left(\frac{N_{spk}}{N_{tot}(N_{tot} - N_{spk})}\right)^{1/2},$$

using the fact that N_{spk} follows the binomial distribution to find N_{spk} successes among N_{tot} trials.

V. ELECTRON DRIFT VELOCITY IN A dc FIELD

Let us consider what happens, under the influence of a dc field, to the electrons which the cosmic-ray particle produced between the electrodes. We assume that the retarded electrons have been created very quickly so that we can neglect them together with the secondary electrons. Then only instantaneous primary electrons need to be considered, they are homogeneously distributed across the gap with linear density n, but only $n(b-d)$ are within the sensitive region. If the clearing field is parallel to the high-voltage pulse, the mean number of electrons that can independently cause a spark at a time t after the ionization is

$$X_+(t) = n(b - d - vt),$$

because the electric field clears the gap with electron drift velocity v. With antiparallel dc field, there will be no change in the number of electrons until they have traversed the distance d necessary for spark development, then it decreases at the same rate:

TABLE II. Some dimensions of the apparatus.

Area of spark chamber	90×90 cm^2
Gap between electrodes	10 mm
Length of high-voltage pulse	0.1 μsec
Height of high-voltage pulse	5–10 kV
Area of scintillation counters	40×40 cm^2
Thickness of aluminium electrodes	20 μm

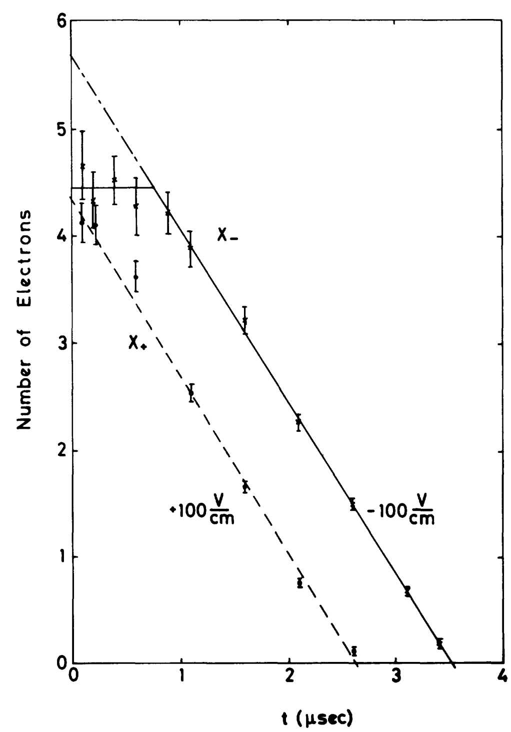

FIG. 2. Number of primary electrons under the influence of a dc field as a function of time. $X_{+,-}$ refers to a parallel, antiparallel dc field with respect to the HV pulse. Helium gas with 0.85% N_2 admixture for quick (> 20 μsec^{-1}) deexcitation of metastable helium atoms; HV pulse = 6.9 kV, 0.1 μsec long; pressure, 785-mm Hg.

$$X_-(t)=n(b-d), \quad t \leq d/v$$

$$X_-(t)=n(b-vt), \quad t \geq d/v .$$

If the high-voltage pulse is applied to the electrodes at time t after the cosmic-ray particle, $X_+(t)$ and $X_-(t)$ can be measured. An example is shown in Fig. 2. We note that the drift velocity is essentially determined by the interelectrode distance b and the time at which $X_-(t)$ vanishes, whereas the total number of primary electrons in the gap (nb) is given by the straight-line extrapolation of the inclined part of $X_-(t)$ to $t=0$. This number should be independent of the dc field, and, in fact, it is. Figure 3 gives an example of a measurement of $X_-(t)$ for three different dc fields, and the extrapolated number of primary electrons is seen to be identical within statistical errors. Varying the size of the HV pulse did not alter any of the results.

Electron drift velocities v were determined in this way for helium including a small admixture of 0.3–0.9% N_2 or Ar for the necessary deexcitation of metastable He atoms. The influence of these contaminants on v was studied and found to be smaller than the statistical errors of this measurement. In Fig. 4, the results are shown as a function of E/p (the ratio of the electric field over the gas pressure) and compared to the values obtained by Crompton, Elford, and Jory[3] and by Pack and Phelps[4] using the shutter method. The agreement is quite satisfactory and indicates that the spark chamber method described here is a useful technique for the measurement of drift velocities.

Earlier attempts to determine electron drift velocities in spark chambers include the work of Burnham *et al.*,[5] and Fischer[6] (see also references cited therein) with emphasis on the relative variations caused by the admixture of alcohol. In the present section it was seen that even absolute values can be obtained if one relies on the measurement of the mean number of electrons as outlined above.

VI. PRIMARY IONIZATION

If the total number of primary electrons in the gap (nb) is due to gas ionization, it ought to be proportional to the gas pressure. Measurement of the pressure dependence reveals that it is linear (Fig. 5), but there is a residual contribution of 15% of the value for helium at 1 atm owing to the electrons produced in the aluminium foils.

In order to obtain the true number of primary electrons caused by gas ionization, a further correction factor of 0.87 ± 0.02 is caused by triggers associated with several cosmic-ray particles which traversed the chamber simultaneously.

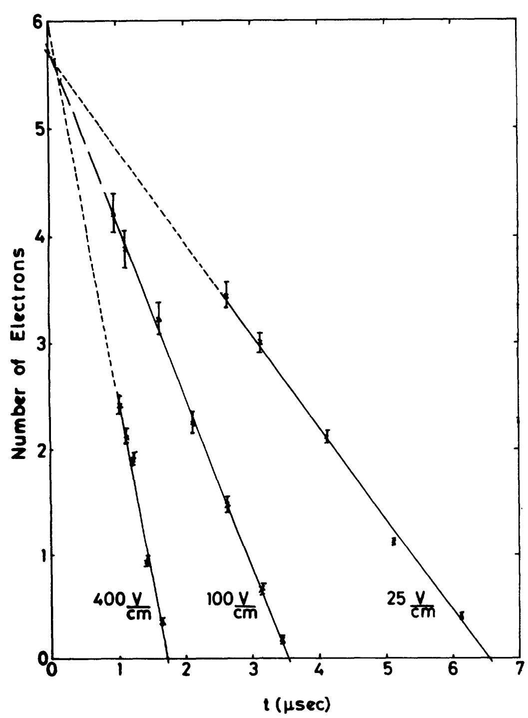

FIG. 3. Number of primary electrons under the influence of three different dc fields antiparallel to the HV pulse. The straight lines extrapolate to the same number of originally produced electrons. Same conditions as for Fig. 2.

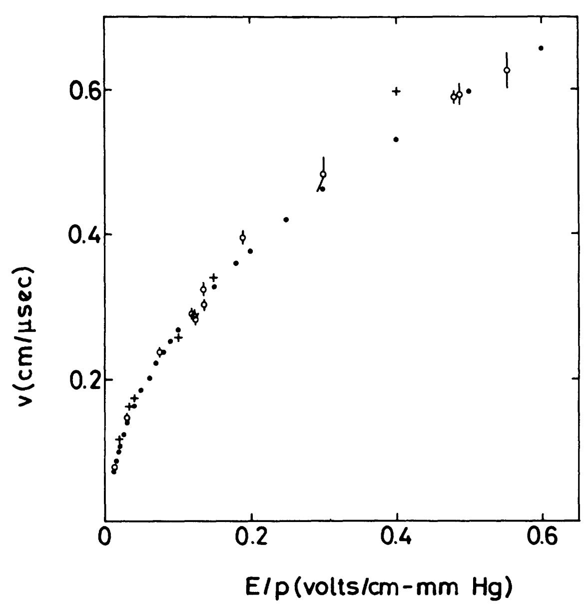

FIG. 4. Electron drift velocities in helium measured with the spark chambers (ϕ), compared to the values of Crompton *et al.* (Ref. 3) (·), and of Pack *et al.* (Ref. 4) (+).

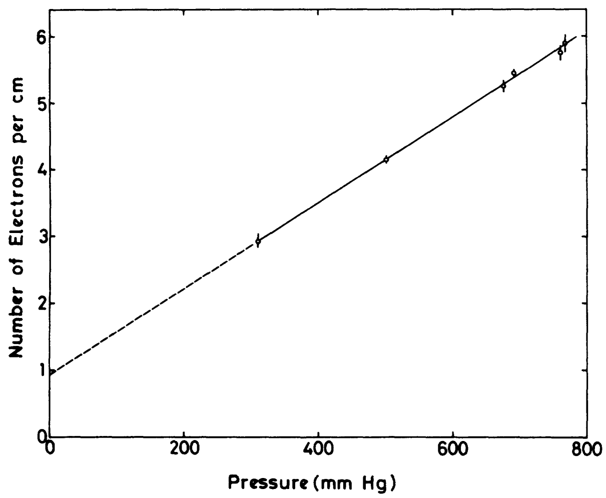

FIG. 5. Primary ionization in the helium spark chamber as a function of gas pressure, indicating a residual contribution from the aluminium foils.

Their frequency (which depends on local conditions) was determined by visually observing 1000 triggers in a set of four chambers.

After applying these two corrections, the total number of primary electrons due to helium ionization at 1 atm and 0°C by the full spectrum of cosmic-ray particles is $I_p = 4.35 \pm 0.17$. Similar measurements were done with a mixture of 70% Ne and 30% He, commonly used in particle-physics spark chambers, and the corrected value here was $I_p = 9.4 \pm 0.4$ yielding 11.7 ± 0.5 for pure neon. (In terms of the definitions of Sec. II, $I_p \equiv N_p^\zeta$.)

Since the primary ionization is known to depend on the energy of the traversing particle, it would have been best to move the apparatus into the beam of some accelerator, but this proved to be impossible. Instead we could use the CERN-Munich wire-spark-chamber spectrometer with automatic read-out of spark positions, which was installed at the CERN proton synchrotron at the time. These chambers are constructed in a similar way to that described in Sec. IV, but the electrodes are grids of parallel copper wires with diameter of 0.1 mm.[7] The momentum of the particles was determined to better than 1% by the magnets in the apparatus. In addition, there were two threshold Čerenkov counters in front of and one behind the chambers to identify individual particle masses from the mixture of electrons, muons, pions, kaons, and protons that were contained in the beam. Seven runs at 5, 8, and 17 GeV/c with different particle triggers were recorded on magnetic tape and later played back on a computer display screen picturing the spark positions of 18 consecutive chambers. For one run, each chamber had N^i_{spk} sparks and N_{trig} triggers, only counting the sparks that belonged to the same beam track; the average number $\bar{X}$ of primary electrons per chamber was then calculated as

$$\bar{X} = \frac{\sum_{i=1}^{18} [(N_{trig} - N^i_{spk}) \ln(1 - N^i_{spk}/N_{trig})]}{\sum_{i=1}^{18} (N_{trig} - N^i_{spk})} .$$

The operating conditions of the chambers were the ones under which the spectrometer normally ran: 68% Ne, 29% He, and 3% isopropylalcohol, at 1 atm, dc field 250 V/cm [opposite to high-voltage (HV) pulse], total delay between particle and HV pulse 0.6 μsec; these conditions were the same for all runs. The values of $\bar{X}$ obtained for the different ratios $\beta\gamma$ = (particle momentum)/(rest mass) are plotted in Fig. 6 on a logarithmic scale. The drawn-out straight line represents a linear dependence of the primary ionization on $\ln(\beta\gamma)$ which is the approximation of Bethe's formula for extreme relativistic velocities. The point with

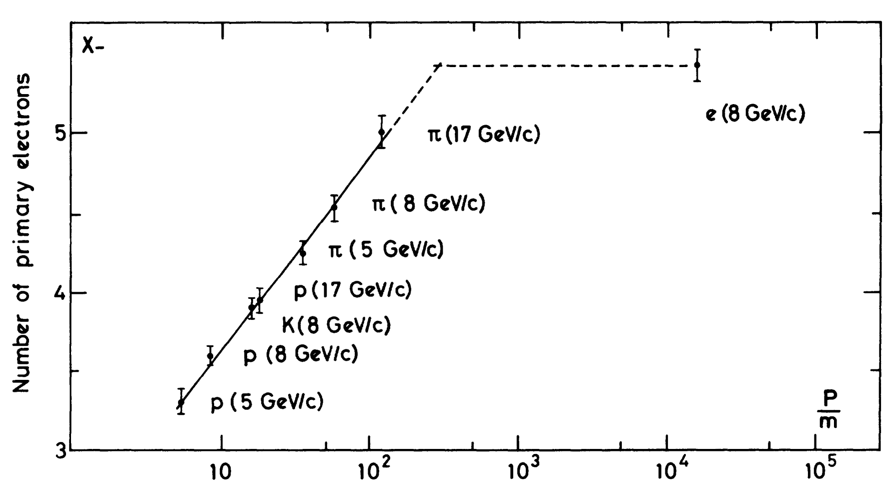

FIG. 6. Relativistic rise of the primary ionization, measured with large wire spark chambers. The mean number of free electrons, determined from the chamber efficiency, is plotted against the ratio $\beta\gamma$ equaled to particle momentum over rest mass, determined with the spectrometer.

the highest $\beta\gamma$ (electrons of 8 GeV/c) falls below this line owing to the density effect first described by Fermi,[8] and the one belonging to the lowest $\beta\gamma$ (protons of 5 GeV/c) is very close to the minimum ionization expected from the measured points. The ratio between highest and lowest ionization is 1.6 with statistical error 0.05, a value similar to the results of other authors (for a review, see Crispin and Fowler[9]). It is possible that the true value is somewhat larger owing to the neglect of electrons created in the wire electrodes.

VII. RETARDED IONIZATION

Up to this point, the ionization caused by the deexcitation of metastable helium atoms had been eliminated by small but sufficient admixtures of a molecular gas so that the retarded electrons behaved as if instantaneously produced. We will now reverse the procedure and find out what happens when the rare gas is so clean and the dc field so high that all the instantaneously liberated electrons have left the gap when there are still many metastable atoms around which produce free electrons.

Although it is not completely clear how the metastables are excited they will be uniformly distributed across the gap (coordinate ξ) with linear density a and are deexcited exponentially in time with a mean life of $1/\lambda$. Under the influence of the dc field the electrons travel with velocity v once created. The integration has to take into account

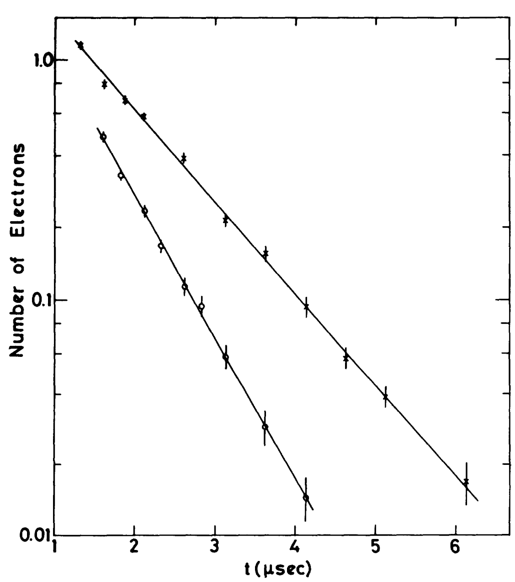

FIG. 7. Evidence for a strong contribution of retarded ionization: Exponential decrease of the mean number of free electrons after a strong dc field has cleared the gap of primary electrons (ϕ for Helium; ∤ for Henogal).

that at a later time t, when the HV pulse arrives, some of them have drifted out of the sensitive region (between 0 and $b-d$). This can best be described with the help of a step function S defined for the interval $X_1 \ldots X_2$ ($X_2 > X_1$) as follows:

$$S(X; X_1, X_2) = 0 \quad \text{if } X \leq X_1 \text{ or } X \geq X_2$$

$$S(X; X_1, X_2) = 1 \quad \text{if } X_1 \leq X \leq X_2 .$$

The total number of retarded electrons in the sensitive region at time t (HV pulse opposite dc field) is then given by the integral

$$A_-(t) = \int_0^t d\tau \int_0^b d\xi \, a\lambda e^{-\lambda\tau} \times S(\xi; (t-\tau)v, (t-\tau)v + (b-d))$$

which, at the time of interest, $t > b/v$, is equal to

$$A_-(t) = ae^{-\lambda t}[(v/\lambda)(e^{\lambda b/v} - e^{\lambda d/v}) - (b-d)] .$$

We notice that this number varies as an exponential of the delay time. In a series of measurements under the conditions described, the number of free electrons was measured as a function of delay time; the result is depicted in Fig. 7. The points, drawn on logarithmic scale, lie nicely on a straight line representing mean lifetimes of $1/\lambda = (0.72 \pm 0.02)$ μsec (helium) and $1/\lambda = (1.14 \pm 0.02)$ μsec (neon-helium). Evidently there is a clean effect of retarded ionization. While we defer the systematic discussion of the measured decay constants λ and their variations to Sec. VIII, we will first concentrate on the number of metastable atoms present after the passage of the high-energy particle.

This is given by the product ab and can be determined with the help of the above formula from measurements as in Fig. 7; the constants v and d are to be obtained from the method described in Sec. V.

After applying corrections for the cases of several cosmic-ray particles traversing the apparatus simultaneously (factor of 0.87 ± 0.02, see Sec. VI) and normal gas conditions, we found the values given in Table III. They indicate that there is an appreciable contribution of retarded as compared to primary instantaneous ionization caused by cosmic-ray particles. In terms of the electron com-

TABLE III. Number A_0 of metastable atoms per centimeter and ratio of retarded to primary electrons caused by a cosmic-ray particle (full energy spectrum).

Gas (1 atm, 0 °C)	A_0	A_0/N_0
Helium	1.9 ± 0.2	0.4
70% neon + 30% helium	5.9 ± 0.4	0.6

TABLE IV. Different mean lifetimes $1/\lambda$ of metastable atoms in helium gas caused by different admixtures.

Pressure (Torr)	O_2 (ppm)	H_2O (ppm)	N_2 (ppm)	Sum (a) (ppm)	Sum (a) (10^{-16} cm^{-3})	λ (μsec^{-1})
737	34	60	200	294	0.718	1.18 ± 0.04
729	6	63	305	374	0.905	1.39 ± 0.04
833	47	68	337	452	1.230	1.72 ± 0.04

ponents defined in Sec. II, $A_0 \equiv A_s^g + A_s^f + A_p^g$ and $N_0 \equiv N_p^g + N_p^f$.

So far, we have neglected the influence of electron attachment to be expected from the molecular-gas contamination. Using the measured concentrations we estimate that the true values for A_0 might be $\approx 10\%$ higher than that states in Table III.

Although the retarded ionization caused by high-energy particles was expected to exist (Jesse and Sadauskis[10]), this is, to our knowledge, the first time it has been isolated.

VIII. LIFETIME OF METASTABLE ATOMS

The rate at which the retarded ionization is produced is proportional to the inverse mean lifetime of the metastable atoms. These could, in principle, be deexcited in collisions with molecules of low enough ionization potential or in triple collisions with pairs of rare-gas atoms. In the first case, the inverse mean life must be proportional to the density of the molecules; in the second, it is expected to vary with the square of the rare-gas density.

Since the chamber and the gas system were not designed for extreme gas purity, we were satisfied to look only for any variation of the mean life with the density of some molecular-gas contamination. Table IV contains the results of three different runs in helium with admixtures consisting mainly of N_2 and some O_2, H_2O, as measured with the gas spectrometer; for simplicity, these have been added together. One notices that there is, indeed, a change with contamination. The plot of Fig. 8 shows that the inverse mean life of the metastables is approximately a linear function of the density of the admixture with a residual value of $\lambda_0 = (0.4 \pm 0.1)$ μsec^{-1} for zero contamination. If due to the three-atom collisions, this value would be about a factor of 2 or 3 larger than the value given in the literature.[11,12]

From the linear part in Fig. 8 an average cross section σ for the reaction

$$\text{He(metastable)} + M \rightarrow \text{He} + M^+ + e^-$$

can be determined, where M stands for the molecule which was N_2 in ~75% of the cases. Using a relative velocity of 1.33×10^5 cm sec^{-1} and the formula

$$\sigma = \frac{\lambda(a) - \lambda_0}{a v_{\text{rel}}},$$

we obtain a cross section of $\sigma = (7.9 \pm 0.8) \times 10^{-16}$ cm^2. This compares with values for N_2 of $\sigma = 6.4 \times 10^{-16}$ cm$^2 \pm 50\%$ as measured by Benton *et al.*[11] and $\sigma \approx 10 \times 10^{-16}$ cm^2 by Colegrove and Franken[13] with a spectroscopic method.

IX. CONCLUSION

This paper has shown that the method to determine the number of free electrons, using the inefficiency of a spark chamber, is able to produce meaningful, even precise results. From the point of view of a high-energy physicist this means that this instrument is well understood, even in the form of large wire chambers. For the study of gas phenomena as such (ionization, electron movement, and deexcitation of metastable atoms) we may conclude that the spark chamber is a useful tool because of its inherent simplicity.

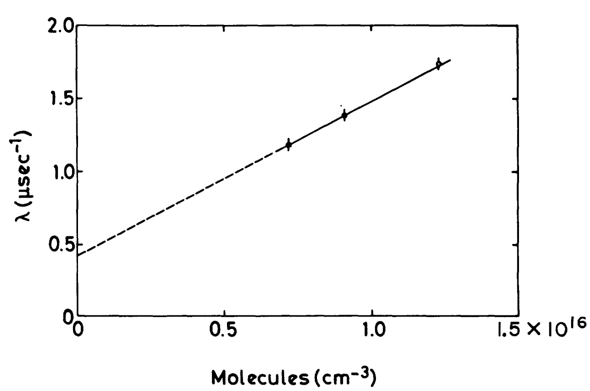

FIG. 8. Decay constant λ for helium from Table IV as a function of the density of the molecular admixture, showing approximate linearity.

*A more detailed account of this work is contained in the Ph.D. thesis by K. Söchting, University of München, München, Germany, 1973.

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