Relativistic increase of the specific primary ionization in noble gases

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The relativistic increase of the specific primary ionization in the noble gases He, Ne, Ar, Kr, Xe, and henogal (a mixture of 30% He and 70% Ne) is investigated using a low pressure wire spark chamber. The results are in good agreement with the theoretical predictions which take into account the effect of the polarization of the medium.

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1. INTRODUCTION

The increase of the number of ionizing collisions of relativistic charged particles in gases (the so-called relativistic increase of the primary ionization) together with the relativistic rise of the total ionization can be used to identify particles in experiments in high energy physics.[1-3] This idea is now being realized, for example, in spectrometers based on streamer chambers.[4,5] As is well known, measurements of the primary ionization have the advantage that its fluctuation have a purely Poisson distribution, in constrast to those of the total ionization.

Meanwhile, the relativistic increase of the primary ionization has been measured only in helium[2,6,7] and in helium–neon mixtures.[3,5,8] The results of these studies are in agreement with the predictions of the theory which takes into account the effect of the polarization of the medium.[1,9] Up to the present time, measurements in heavy gases have been made only in the vicinity of the primary ionization minimum, that is, for values of the Lorentz factor $\gamma = E/mc^2 \leqslant 4$ (Refs. 10–14).

Therefore, the systematic investigation of the relativistic increase of the primary ionization in gases with a different atomic number is of interest both for verifying the existing theoretical predictions and for selecting the optimal possibilities for high-energy-particle identification. Preliminary results of our measurements were published earlier.[15]

2. THE TECHNIQUE AND THE EXPERIMENTAL RESULTS

The relativistic rise of the primary ionization in the pure noble gases He, Ne, Ar, Kr, Xe and a mixture of 30% He and 70% Ne (henogal) was measured using a technique that we have recently developed—the low pressure spark chamber with wire electrodes.[13,14] Using this chamber it is possible to measure the primary ionization even in gases with a high electron diffusion coefficient, since the drift of electrons from the interelectrode gap is to a considerable degree cancelled by the back diffusion of electrons produced outside the gap. For a spark discharge to occur in a wire spark chamber it is sufficient that a single electron appear in its working volume. Therefore, the spark chamber efficiency η, that is, the ratio of the number of firings to the total number of passages of single charged particles through the chamber, is a function of the primary ionization n produced by these particles in the gas, which is

$$n = -\ln(1-\eta). \tag{1}$$

Therefore, the primary ionization can be determined from the measured efficiency of the spark chamber.

In the experiment we used two identical spark chambers with interconnected gas volumes, each with a 1 cm discharge gap and with wound electrodes of BrB-2 beryllium bronze wire of diameter 90 μm and pitch 1 mm. The chambers were filled with a pure noble gas at a pressure below atmospheric. They were alternately exposed to a monenergetic beam of electrons from the FIAN synchrotron and electrons of energy 1.2–2.2 MeV ($\gamma \approx 4$) from a radioactive $Sr_{38}^{90}(Y_{39}^{90})$ source. By changing the current in the windings of the deflecting magnet it was possible to vary the momentum of the beam of the accelerator electrons in the range 30–570 MeV/c and thereby to make measurements in the relativistic rise region and at the expected start of the primary ionization plateau. The beam pulse duration was 0.5 sec and the repetition frequency was once in five seconds.

The beam was shaped by four scintillation coincidence counters S_1, S_2, S_5, and S_6, each 3 mm thick, and two anticoincidence counters $\bar{A}_3$ and $\bar{A}_4$ with a central aperture of diameter 25 mm. It was then passed successively through the two spark chambers located between the counters $\bar{A}_3$ and $\bar{A}_4$. The distance between the end counters S_1 and S_6 was about 7 m. All the counters and the spark chambers were aligned by means of a laser. The total thickness of the matter in front of the spark chambers (7 m of air, 0.6 cm of scintillator, and the entrance windows, each 50 μm of aluminum) amounted to ~0.05 of the radiation length.

In the cases of the accelerator beam and the β source, respectively, the spark chambers were triggered by the coincidences $S_1S_2\bar{A}_3\bar{A}_4S_5S_6$ and $\bar{A}_4S_5S_6$. The delay times in the channels of all the counters were carefully adjusted and balanced. The spark discharge in each chamber was registered by an FÉU-68 photomultiplier. The time constant of the high-voltage pulse supplied to the spark chambers was 0.2 μsec and its delay time was $t_3 = 0.25$ μsec. All of the control electronics were located near the setup in the experimental hall and the operation of the apparatus was controlled from a remote control

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panel.

The operating stability of the spark chambers was ensured by choosing the amplitude of the high-voltage pulse to lie in the middle of the plateau of the counting-rate curve (the length of the plateau as a function of the composition and pressure of the gas was 1 to 3 kV; see Ref. 14) and by maintaining the gas pure by constant forced circulation through a purification system containing zeolite and potassium chips heated to 450–500°C. Periodic checks of the gas purity using a KhLM-2MD chromatograph showed that the partial pressures of the different admixtures did not exceed 10^{-5} atm for xenon). The dead time of the spark chambers after they were triggered was set equal to the pause 5 sec between successive beam pulses. This time proved to be sufficient to prevent false discharges due to the de-excitation of long-lived mestastable states.

It was verified in control measurements that false triggerings and counting errors of the spark chambers due to the presence of electrons or hard γ rays traveling simultaneously in the beam did not exceed several tenths of a percent. The accuracy of the operation of the spark chambers was also checked by comparing their efficiencies, which proved to be equal.

In order to introduce corrections for false discharges due to ionization of the gas by "old" particles, working exposures were alternated with control exposures in which the spark chambers were triggered randomly using a periodic-pulse generator with the same radiation-source intensity and dead time of the system. The measured background from cosmic rays was 0.3% of the firings. All these corrections entered into the total measurement error.

We also studied the contribution of secondary electron emission (δ electrons) from the thin metal windows and the wire electrodes of the spark chambers. For this purpose the dependence of the measured primary ionization in the helium spark chamber on the pressure P of the gas was extrapolated to $P=0$. Figure 1 shows that the measured contribution of electrons from secondary emission per single passage of a charged particle was 0.03 ± 0.07. The upper calculated estimate of the expected δ-electron contribution is 1% and can therefore be neglected. The sizable fraction of secondary-emission electrons found in Ref. 8 is possibly due to the use of spark chambers with solid electrodes.

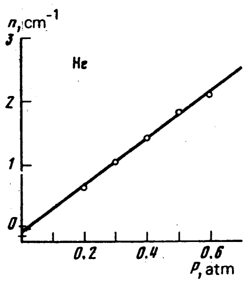

FIG. 1. Primary ionization, n pairs of ions per centimeter, which can be produced by the electrons of a radioactive Sr_{38}^{90} (Y_{39}^{90}) source of mean energy 1.5 MeV per centimeter of path in a helium spark chamber as a function of the pressure of the gas P ($T=293$ K). The experimental data have been corrected for the diffusion of the electrons produced in the gas by a charged particle to the wire electrodes of the spark chamber during the delay time $t_d=0.25$ μsec of the high-voltage pulse. (The correction for the diffusion is 2.5% at $P=0.6$ atm and 4.3% at $p=0.2$ atm). The experimental errors do not fall outside the circles.

In an earlier study[14] we showed that for absolute measurements of the primary ionization it is necessary to extrapolate the data obtained for different high-voltage pulse delay times t_d to $t_d=0$.[14] Since in the present experiment $t_d=0.25$ μsec, the measured primary ionization, due to the fact that the electrons produced by the particle that passes through the gas diffuse to the electrodes of the spark chamber, turns out to be 2.5–13% less than the true value, depending on the sort and pressure of the gas. A favorable circumstance, however, is that in our experiment we carried out relative measurements, that is, the primary ionization was measured relative to its minimum value at $\gamma=4$. Furthermore, the calculated spectra of the energy trnasfers in collisions of relativistic charged particles with noble gas atoms depend weakly on γ (Ref. 16). Therefore, the diffusion of secondary electrons in the gas during the delay time of the high-voltage pulse has exactly the same effect for both $\gamma=4$ and $\gamma>4$, and the results of relative measurements of the relativistic increase of the primary ionization do not depend on t_d.

Our experimental data on the relativistic rise of the specific primary ionization in noble gases are presented in Table I and in Fig. 2, where they are compared with the results of other studies and with the theoretical predictions.

3. CALCULATIONS OF THE RELATIVISTIC INCREASE OF THE PRIMARY IONIZATION IN GASES

There have been several attempts to theoretically describe the primary ionization of gases under the influence of relativistic hcarged particles. The Bethe formula[17] was obtained for atomic hydrogen and does not take into account the effect of the medium. Its use for other gases leads to the values of the minimum primary ion-

TABLE I. Relativistic rise of the primary ionization in the noble gases.

gas	P, atm	(dn/dx)(min), cm^{-1}*	$(dn/dx)_{\gamma=10^3}/(dn/dx)_{\gamma=4}$**	
			Experiment	Theory[1,9]
He	0.40	1.36±0.02	1.56±0.04	1.55
Ne	0.15	1.71±0.02	1.67±0.03	1.67
Ar	0.07	1.86±0.03	1.58±0.02	1.58
Kr	0.05	1.38±0.03	1.58±0.03	1.63
Xe	0.04	1.79±0.04	1.63±0.02	1.62
30% He+70% Ne	0.15	1.34±0.04	1.72±0.03	1.68

*Minimum ($\gamma=4$) specific primary ionization[14] at P (atm) and $T=293$ K. To obtain the minimum primary ionization under normal conditions the data given in this column must be divided by $0.932P$.

**The relativistic rise of the primary ionization at $\gamma=10^3$ is several percent lower than at the plateau (see Fig. 2).

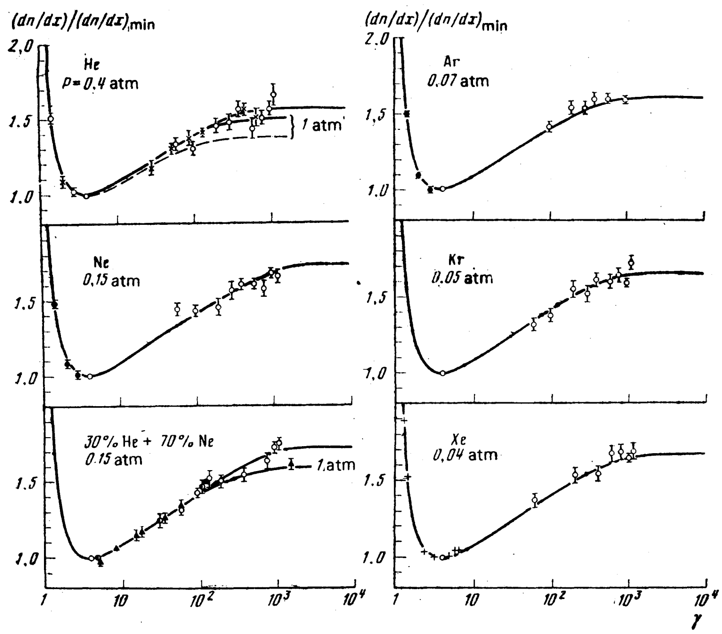

FIG. 2. Relativistic rise of the specific primary ionization in noble gases as a function of the Lorentz factor γ at $T=293$ K. Pressure $P<1$ atm; ○—present study, ●—Ref. 10, +—Ref. 12; $P\approx 1$ atm: ◐—Ref. 5, x—Ref. 6, ▲—Ref. 8. The solid-line curves were calculated using formulas (2)—(5). The dashed line shows the calculation of Budini *et al.*[18] for He at $P=1$ atm. The experimental data of the present study and also those of Refs. 6, 10, and 12 are normalized to the calculated curves at the ionization minimum, while those of Refs. 5 and 8 are normalized at $\gamma=8.3$ and $\gamma=17.1$, respectively.

ization that are off by 20% in He and Ne and by 100–200% in Ar, Kr, and Xe. The calculations by Budini *et al.*[18] for helium, which take into account the polarization of the medium, understate considerably the expected relativistic increase of the primary ionization (Fig. 2).

In Refs. 1 and 9 a method was proposed for calculating the specific primary ionization in a polarizable medium. The data on the oscillator strengths of atomic transitions needed for this were calculated on the basis of the differential cross section for photoionization. According to Ref. 9, the specific primary ionization (dn/dx) which can be produced by singly charged relativistic particles in a gas is given by an expression close to the Bethe formula, but corrected for the polarization of the medium and having parameters that depend on the particular gas:

$$\frac{dn}{dx}=\frac{A_1P}{\beta^2(T/273)}\left[A_2+\ln\frac{\beta^2}{(1-\beta^2)}-\beta^2-\Delta\right]\ [\mathrm{cm}^{-1}]\ . \tag{2}$$

Here P (in atm) and T (K) are the pressure and temperature of the gas, β is the ratio of the particle velocity to the speed of light, and Δ is the correction for the effect of the density of the medium. The values of the coefficients A_1 and A_2 are given in Table II together with the values of the other parameters that will be used below.

For $\log\gamma\leqslant X$, where X depends on the atomic number and on the pressure and temperature of the gas, the polarization of the medium is negligibly small. For $\log\gamma > X$ it is necessary to take into account the correction for the density effect. The calculation of this correction can be simplified if the following interpolation formula, similar to that proposed by Sternheimer for the correction due to the polarization of the medium in calculating the specific energy losses,[19] is used:

$$\Delta=\begin{cases}0, & \lg\gamma\leqslant X\\ 4.606\lg\gamma+B+C(Y-\lg\gamma)^d, & X<\lg\gamma<Y.\\ 4.606\lg\gamma+B, & \lg\gamma\geqslant Y\end{cases} \tag{3}$$

At $\log\gamma>Y$ the primary ionization levels off to form a plateau. The parameters B, C, and d for pressure P and temperature T of the gas are given by the following relations:

$$\begin{aligned}B&=(A_2-1)-(dn_0/dx)^{(\mathrm{min})}R/A_1,\\ d&=-4.606(Y-X)/(4.606X+B),\\ C&=-(4.606X+B)/(Y-X)^d.\end{aligned} \tag{4}$$

Here $(dn_0/dx)^{(\mathrm{min})}$ is the minimum specific primary ionization under normal conditions ($P=1$ atm, $T=273$ K), and the values of the relativistic increase $R=(dn/dx)^{(\mathrm{plateau})}/(dn/dx)^{(\mathrm{min})}$ and also of X and Y are obtained from the corresponding values of R_0, X_0, and Y_0 under normal conditions by means of the following expressions:

$$\begin{aligned}R&=R_0-a\lg[P/(T/273)],\\ X&=X_0-0.45\lg[P/(T/273)],\\ Y&=Y_0-b\lg[P/(T/273)].\end{aligned} \tag{5}$$

TABLE II. Calculated specific primary ionization in the noble gases under normal conditions ($P=1$ atm, $T=273$ K).

Gas	He	Ne	Ar	Kr	Xe	30% He + 70% Ne
$\rho\cdot 10^3$, g·cm^{-1}	0.17847	0.90035	1.78370	3.7080	5.8510	0.68379
(dn_0/dx)(min), cm^{-1}	3.5	11.4	25.9	35.4	48.1	9.2
(dn_0/dx)(plateau) cm^{-1}	5.2	18.0	36.2	50.4	67.7	14.5
R_0	1.486	1.575	1.400	1.424	1.408	1.570
A_1, cm^{-1}·atm^{-1}	0.244	0.844	1.828	2.551	3.448	0.679
A_2	11.64	10.89	11.45	11.30	11.28	10.98
a	0.161	0.171	0.164	0.167	0.169	0.170
b	0.39	0.42	0.31	0.25	0.31	0.42
X_0	1.88	1.31	1.50	1.47	1.40	1.79
Y_0	3	3	3	3	3	3
$-B$	10.66	11.42	9.36	9.47	9.36	11.35
C	1.50	2.53	0.78	0.89	0.89	2.20
d	2.56	1.44	2.82	2.61	2.53	1.79

The values of $(dn_0/dx^{(\min)}$, $(dn_0/dx)^{(\text{plateau})}$, R_0, X_0, Y_0, a, and b are also given in Table II. Using the above relations we can estimate the expected primary ionization at any pressure and termperature when the gas is assumed to be ideal. The accuracy of the interpolation formulas in the transitional region between the logarithmic increase and the plateau is several percent.

4. DISCUSSION OF THE RESULTS

In Fig. 2 we compare the theoretical curves with our measurements of the relativistic rise of the specific primary ionization in noble gases and also with the data from other measurements with a streamer chamber,[5] with a Wilson cloud chamber,[6] with a spark chamber,[8] and with low-efficiency counters.[10,12] As seen from expression (2), in the region of the logarithmic rise, up to the beginning of the influence of the density effect, the results of the relative measurements for any particular gas are independent of the pressure and temperature. Rapid secondary processes in a gas with impurities do not have any effect on the size of the relativistic increase.[1] The experimental data obtained in the various detectors can therefore be compared with one another.

Figure 2 shows that the available experimental data are in agreement with the results of calculations by formulas (2)–(5). The systematic deviations of the measured results from the calculated curve, which were noticed in early studies with a helium streamer chamber,[2] are not observed. Therefore, the results of our and other experiments are in good agreement with the predictions of the theory of ionizing collisions of relativistic charged particles in a medium[1,9] and prove that it can be used to calculate the specific primary ionization in noble gases.

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