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Design of ^{3}He-Filled Fast Proportional Counters*

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Electron drift velocity measurements have been made on helium, helium-CO_2, and helium-CH_4 mixtures in order to determine the optimum design parameters for ^{3}He-filled proportional counters. It is shown that small (<1-in.-diam) counters with neutron detecting efficiencies of greater than 1% at 1 keV and with jitter times of less than 1 μsec are practical. Calculated and measured jitter times for several counters are compared.

INTRODUCTION

Now that ^{3}He is commercially available at a reasonable cost,[1] the interest in ^{3}He counters for neutron detection has been increasing rapidly. Recent work[2] has emphasized their greater neutron efficiency, as compared to $^{10}BF_3$ counters, without an appreciable increase in gamma-ray sensitivity. Another important specification of these counters, particularly for neutron time-of-flight or coincidence work, is their *jitter time* (the maximum time between the ionizing event in the gas and the formation of the voltage pulse). It should be noted that the jitter time is related to, but not the same as, the risetime of the pulse. The latter depends on the length of the track in the gas and on the orientation of the track with respect to the center wire. Reducing the length of the track by adding a gas with a high stopping power, such as krypton, will reduce the pulse risetime. On the other hand, the jitter time is the time it takes for a track formed near the outside of the counter and parallel to the center wire to drift into the center wire region where the multiplication process begins.

For a cylindrical counter of diameter $2b$ and center wire diameter $2a$, the jitter time is given by

$$\tau=\int_a^b \frac{dr}{v(r)}, \tag{1}$$

where $v(r)$ is the electron drift velocity and r is the radial distance from the center of the counter. Elementary kinetic theory[3] predicts that the drift velocity is a monotonic function of the ratio of applied electric field E to the gas pressure p. With an applied voltage V_0, the field is given by

$$E=(V_0/r)(\ln b/d)^{-1}. \tag{2}$$

Equations (1) and (2), together with measurements of v as a function of E/p, are all that is needed to determine τ. A recent measurement of the jitter time[4] for a 6-atm, 0.950-in.-diam pure ^{3}He-filled counter[5] with a 2-mil (0.002-in.) center wire gave 3.75±0.1 μsec—much too long for use in most coincidence or time-of-flight systems.

The inherent resolution of the BNL fast chopper time-of-flight system is, at present, limited by the minimum neutron burst width of 1 μsec. Therefore, it would be advantageous to design the most efficient counters with jitter times of less than 1 μsec. τ may be reduced by decreasing the counter diameter, with, however, a corresponding reduction in efficiency, by increasing the center wire diameter which increases the field throughout the counter, and by the addition of a small amount of polyatomic gas, such as carbon dioxide or methane. The drift velocity is proportional to λ/u where λ is the electron collision mean free path and u is the mean electron agitation velocity.[3] The addition of a polyatomic gas decreases u, which consequently increases λ (the Ramsauer effect) in all the noble gases except helium[6] where the decrease in u results in a decrease in λ. However, measurements that have been made on λ vs u for helium[6] indicate that we might expect a net increase in v by a factor of about two. The addition of a polyatomic gas will also allow a higher operating potential and, therefore, a higher field in the counter. In order to optimize the design parameters, a more detailed study of the electron drift velocity and operating voltage conditions was undertaken.

ELECTRON DRIFT VELOCITY MEASUREMENTS

The equipment used to measure the electron drift velocity is similar to that described by Rossi and Staub[7] and is shown in Fig. 1. A well collimated beam of alpha particles is directed parallel and very close to one plate of a parallel plate ionization chamber. The output pulse from the chamber is amplified and then displayed on an oscilloscope where it is photographed. It is easy to show that the induced charge increases linearly until the electrons drift to the upper plate. The drift velocity is then given simply by $v=d/t$, where d and t are defined in Fig. 1. Except for

* Work supported by the U. S. Atomic Energy Commission.
[1] 15¢/cm^3 at STP from Mound Chemical Corporation, Miamisburg, Ohio.
[2] W. Mills, Jr., R. Caldwell, and I. Morgan, Rev. Sci. Instr. **33**, 866 (1962).
[3] E. H. Kennard, *Kinetic Theory of Gases* (McGraw-Hill Book Company, Inc., New York, 1938), pp. 464–475.
[4] J. L. Friedes and R. E. Chrien, Bull. Am. Phys. Soc. **8**, 39 (1963).
[5] Texas Nuclear Corporation, Serial number TN115.
[6] S. C. Brown, *Basic Data of Plasma Physics* (Technology Press, Cambridge, Massachusetts, 1959), pp. 1–10.
[7] B. Rossi and H. Staub, *Ionization Chambers and Counters* (McGraw-Hill Book Company, Inc., New York, 1949), pp. 56–63.

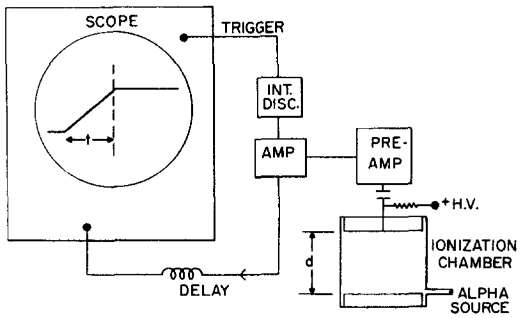

FIG. 1. Experimental equipment for the measurement of electron drift velocities.

methane, the corrections to the measured time due to amplifier risetime are negligible. For methane, which is very fast, the corrections are of the order of 30%.

The results of our measurements of the electron drift velocity in helium, methane, helium-CH_4, and helium-CO_2 mixtures are shown in Fig. 2. All gases were obtained from the Matheson Corporation. The grades used were "Bone Dry" lecture bottle CO_2, "Ionization" grade He, and "Purified" grade CH_4. No further purification was performed. All measurements were taken with 1 atm total pressure. The errors shown are due to the uncertainty in d because of the finite solid angle of the collimator and to the uncertainty in determining t from the oscilloscope photographs. The over-all accuracy is estimated to be 10–15%. Our agreement, for methane, with the previously reported results of English and Hanna[8] is very good. However, for helium we obtain values of v considerably higher than those of Bowe.[9] If we use Bowe's electron drift velocity data and calculate the jitter time, we obtain values which are larger than the measured jitter times by a factor of about two. The relevant numbers are shown in Table I for the three commercially obtained pure ^{3}He counters. The jitter time measurements will be described below. The calculated jitter time depends critically on the shape of the v vs E/p curve for small E/p. Reasonable extrapolation of our data to low E/p values leads to results consistent with the measured jitter times. The extrapolations used are shown in Fig. 2, and the results of the calculations using these curves are listed in Table I. The calculated jitter times, using the present results for the drift velocity for the counters with the He+3%CO_2 mixture, agree very well with the measured jitter times, as is also shown in Table I.

The drift velocity data for the helium mixtures show little improvement over pure helium in the low field region. The great improvement in using CO_2 or CH_4 comes from the increased voltage V_0 that can be used.

JITTER TIME MEASUREMENTS

We measured the jitter time by observing the delayed coincidences between the neutrons and the 4.43-MeV gamma rays from a Pu-Be source. In a Pu-Be source, a ^{9}Be nucleus captures an alpha particle forming ^{13}C which decays via neutron emission to ^{12}C or ^{12}C*. The gamma-ray de-excitation of the ^{12}C* nucleus is very rapid and, therefore, the source produces coincident neutrons and gammas. The experimental setup is shown in Fig. 3. The gamma rays are detected by a 8×6-in. NaI crystal, and the neutrons by the ^{3}He counter under test. Care has to be taken

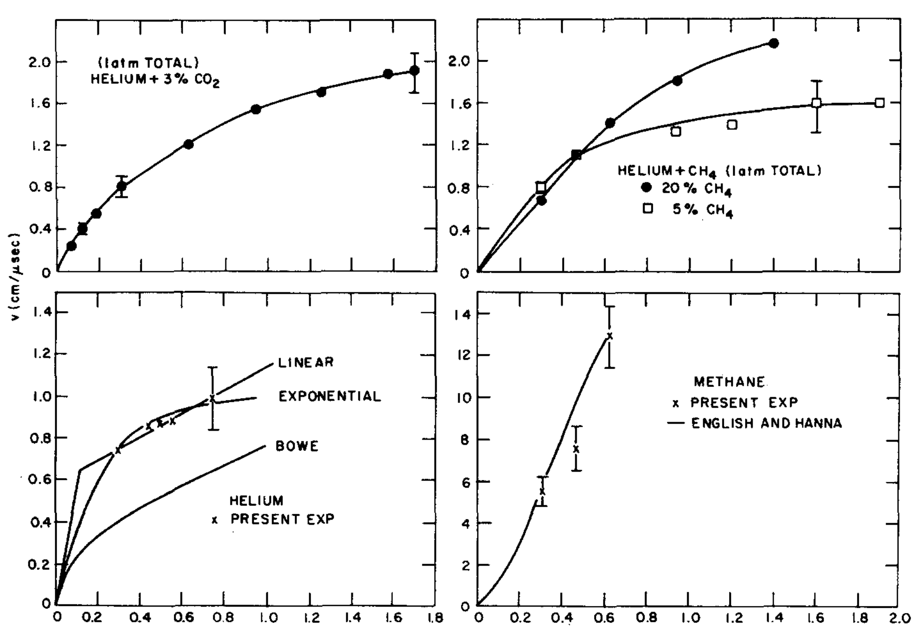

FIG. 2. The measured electron drift velocities as a function of E/p for helium, methane, helium-CO_2, and helium-CH_4 mixtures. All measurements were taken at 1 atm total pressure. For helium the exponential approximation to the present data is given by $v=1-\exp(-4.63\ E/p)$ cm/μsec, and the linear approximation by $v=5.5(E/p)$, for $E/p<0.12$ and $v=0.58+0.56(E/p)$, for $E/p>0.12$ V/cm/mm Hg.

[8] W. N. English and G. C. Hanna, Can. J. Phys. **31**, 768 (1953).
[9] J. C. Bowe, Phys. Rev. **117**, 1411 (1960).

TABLE I. Comparison between calculated and measured jitter times.

Counter[a]	$2a$ (mils)[b]	$2b$ (mils)	Gas filling	V_0 (V)	Measured τ (μsec) n-γ Coincidences	Measured τ (μsec) Chopper	Calculated τ (μsec) Present data Linear	Calculated τ (μsec) Present data exponential	Calculated τ (μsec) Bowe
TN219	6	960	10 atm ^{3}He	2110	2.45±0.1	1.98±0.15	2.61	3.52	5.54
TN223	6	960	2 atm ^{3}He	920	1.56±0.1	1.25±0.15	1.60	2.24	3.47
TN115	2	960	6 atm ^{3}He	1050	3.75±0.1	3.46±0.2	3.81	5.09	6.87
A	12	625	10 atm 97% ^{3}He +3% CO_2	5000	0.74±0.05	0.80±0.25	0.78		
R-S	10	625	10 atm 97% ^{3}He +3% CO_2	5000	0.71±0.04	0.72±0.25	0.80		

[a] TN, Texas Nuclear Corporation, A, Amperex Corporation, and R-S, Reuter-Stokes Corporation.
[b] 1 mil = 0.001 in.

to eliminate any neutrons which are scattered and moderated by the surrounding material and detected at a later time. The boral and cadmium sheets minimize this effect. Figure 4 shows two typical delayed coincidence curves. The results of all these measurements are given in Table I, under the column labeled "Measured τ, n-γ coindences."

The distribution function (the shape of the delayed coincidence counting rate curve) depends on the distribution of tracks in the counter and on the functional dependence of $v(r)$. In addition, it depends on the bias setting of the discriminator in the neutron channel, as changing the bias changes the counter sensitivity to events near the wall. However, the jitter time should be independent of bias setting, and this was verified by running three delayed coincidence curves for bias values which varied by a factor of 100.

Because our measured jitter times and those calculated from Bowe's data disagree by a factor of two, we decided to obtain an independent check on our measurements. To do this, the BNL fast chopper facility was used with a 3-m flight path to measure, with each counter, the full-width at half-maximum (FWHM) of the 21-eV resonance in ^{238}U. With this short a flight path the nuclear and Doppler contributions to the observed resonance width are very small, the width being determined approximately by the convolution of the chopper burst width (1 μsec) and the counter time response. Typical results are shown in Fig. 5. The FWHM for all the counters, after small corrections for the flight time across the counter and the nuclear contribution have been made, are given in Table I under the column labeled "Measured τ, Chopper." It should be pointed out that a measurement of the FWHM of the resonance determines the FWHM of the distribution function which is less than the jitter time. However, the results

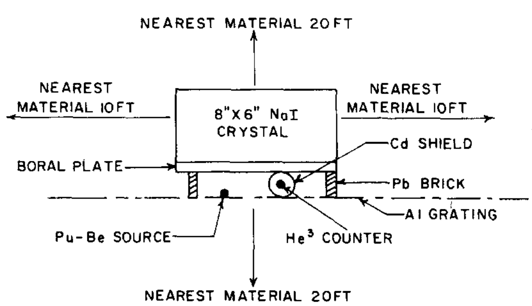

FIG. 3. Experimental setup for the measurement of the jitter time of ^{3}He counters using the n-γ coincidence technique.

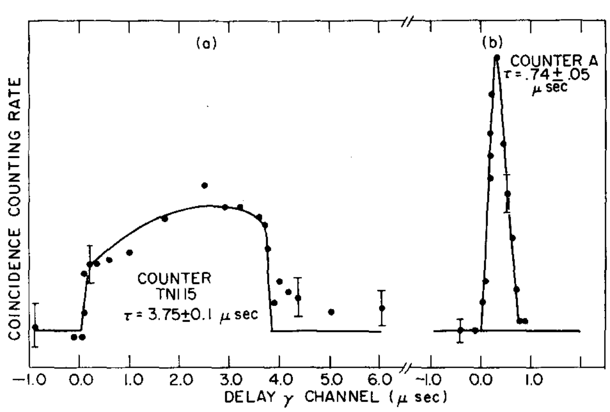

FIG. 4. Typical delayed coincidence counting rate curves for two ^{3}He counters. The physical properties of these counters are listed in Table I.

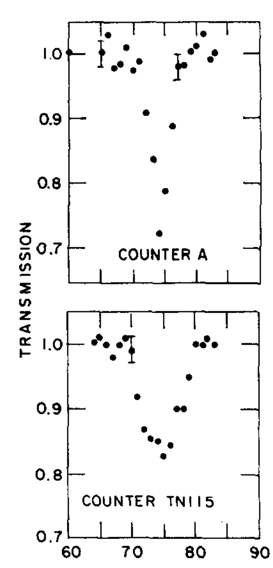

FIG. 5. Transmission data for the 21-eV resonance in ^{238}U for two different ^{3}He counters. The channel width is 0.5 μsec.

are consistent with the more accurate coincidence measurements and definitely disagree with Bowe's data.

OPERATING VOLTAGE

In addition to a knowledge of the drift velocity it is important, for design purposes, to be able to predict the approximate operating voltage of the counter for any given values of the parameters a, b, and p. Multiplication begins when, at some critical radius r_c, the electric field becomes large enough so that the energy gain of the electrons per collision is above some minimum value. Then the same multiplication will be obtained in different counters if the number of collisions between r_c and a is the same for these counters. These considerations lead to an equation relating V_0 to the parameters a, b, and p of the form

$$V_0 = K_1(1+K_2 pa)\ln b/a, \tag{3}$$

where K_1 and K_2 are constants to be determined experimentally. In addition to the five counters shown in Table I, we also used a test counter with $2b=\frac{7}{8}$ in. and $2a=2$ mils. The operating voltage was measured as a function of pressure and was found to be linear in agreement with Eq. (3). Of course, the operating voltage is rather arbitrary, but since only approximate values are needed for the design of counters, its definition is not too critical. We took the operating voltage to be that voltage which produced pulses twenty times the electrical noise of the system, which was about 2×10^{-15} C referred to the input of the charge-sensitive preamplifier. This corresponded to a multiplication of about 10.

If a and b are in mils (0.001 in.), p in atm, and V_0 in V, then Eq. (3), to within 10%, fits all our data. We found that for $2\leq p\leq 10$ atm, $K_1=119$, $K_2=0.080$ for pure He, and $K_1=183$, $K_2=0.104$ for the He+3% CO_2 mixture. Both the A and R-S counters operated at the same voltage even though the center wire diameters were slightly different. This is probably due to the inaccuracy in the determination of the partial CO_2 pressure. This uncertainty is about ±10% which corresponds to a ±200-V difference in the operating voltage.

COUNTER DESIGN

The experimental data on the electron drift velocity in helium +3%CO_2 is fit approximately, for $E/p\geq 0.2$, by $v=1.45\ (E/p)^{\frac{1}{2}}$ cm/μsec. Admittedly, this fit is only good to 10%, but it allows us to write a simple formula for τ,

$$\tau \propto (p\ln b/a)^{\frac{1}{2}} V_0^{-\frac{1}{2}} b^{\frac{3}{2}}. \tag{4}$$

To avoid electrical leakage and breakdown problems it is desirable to keep V_0 below 10 kV. If we fix V_0 and use Eq. (3), then Eq. (4) becomes

$$\tau \propto [p/K_1(1+K_2 pa)]^{\frac{1}{2}} b^{\frac{3}{2}}. \tag{5}$$

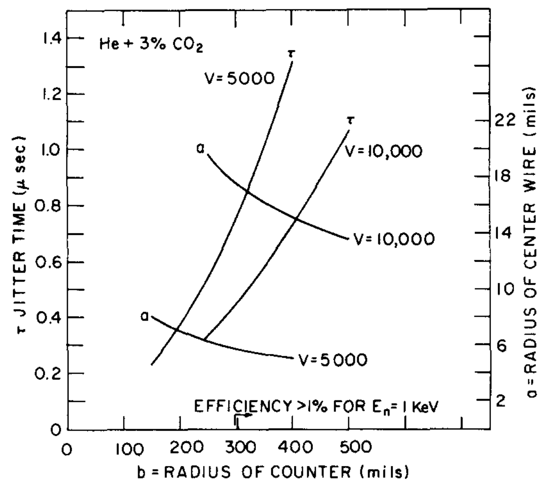

FIG. 6. Calculated values of the jitter time τ vs counter radius b for two different applied voltages for the ^{3}He+3%CO_2 mixture, with $p=10$ atm. Also shown is the required center wire radius a vs counter radius b for the two applied voltages V_0. For a specified jitter time and voltage, the counter radius is determined from the curves labeled "τ". This value of b is then used with the curves labeled "a" to determine the radius of the center wire.

The detection efficiency is proportional to pb and, therefore, we obtain the maximum efficiency by making p as large as possible and adjusting b to give the desired jitter time. The center wire diameter $2a$ is obtained from Eq. (3) for the specified operating voltage. In Fig. 6 we show the results of some calculations for two different operating voltages and $p=10$ atm for the He+3%CO_2 mixture. For these results Eq. (1) was integrated numerically. When $E/p>2$, we took $v=1.9$ cm/μsec. Errors in v for $E/p>2$ cause negligible errors in τ because the time required for the electrons to drift from the region where $E/p=2$ to the maximum E/p of the counter is of the order of 50 nsec. A neutron efficiency of 1% at 1 keV, for the counter in a standard scattering geometry, requires $2bp\simeq 5900$ atm-mils. It is obvious from the results of Fig. 6 that counters with efficiencies greater than this and with jitter times of less than 1 μsec are practical. As an example, suppose we want $\tau=0.8$ μsec and $E_n>1\%$ at 1 keV. Then for $V_0=5000$ V we find $b=310$ mils and $a=5.6$ mils.

ACKNOWLEDGMENTS

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