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Recent Developments in Proportional Counter Technique

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Introduction.

Proportional counters have been used in nuclear physics research for a long time, both in detecting ionizing particles and in measuring their energy. Here it will be sufficient to quote the excellent work of Rossi and Staub[1]) and of Corson and Wilson[2]) as a general introduction on the properties of proportional counters. Constructional details can be found in the book of Korff[3]).

In most of the investigations performed in the past, the particles detected were of the strongly ionizing type, such as protons, alphas, etc., and consequently the energy spent by the particles inside the counter was high, let us say $\gtrsim$ 100 kV (i. e. the input ionization $\gtrsim$ 4,000 ion pairs). In the accounts of these investigations it had been often stated that, for the proper behaviour of proportional counters, the gas amplification factor M must be below a maximum value of about 100. As we shall see below, this statement is certainly incorrect, in its generality, although it may be correct when the input ionization is large. Probably because of this erroneous idea, the potentiality of the proportional counters was not fully made use of until recently; this is remarkable because the outstanding advantage of a proportional counter is just its ability to measure very low energy radiations, which in a non-multiplying ionization chamber would be masked by the amplifier noise. As a matter of fact a considerable fraction of the researches which used proportional counters in the past could have been performed with non-multiplying ionization chambers, although the gas amplification may have been proved useful.

In this paper we discuss mainly problems which could not be solved by a non-multiplying chamber, i. e. problems where it is the gas amplification of the proportional counter which makes it possible to detect and measure a small ionization.

The *detection* of relativistic electrons in a proportional counter at a high multiplication factor has been described in detail by Benson[4]).

In certain applications, such as coincidence work, where fast counting rate is essential, the counter in the proportional region has advantages over the GEIGER counter, because of its small dead-time. In addition its working life is much longer. Nowadays, proportional counters with flowing gas, in which it is possible to introduce a radioactive sample internally (no windows), are frequently used for detecting soft beta particles such as those from C^{14} and H^3 [5]).

Among the pioneer work in *measuring* a small input ionization, by means of a proportional counter, we wish to mention first the unpublished experiments of Bernardini, who more than ten years ago went as far as recognising an intermediate component in the cosmic radiation, but was unable to draw definite conclusions for lack of quantitative information on the proportional counter technique and for lack of a good energy calibration. Again, the fairly recent work of NIKITIN[6]) who obtained a differential spectrum of ionizations brought about by individual cosmic ray particles passing through a proportional counter, is to be mentioned.

In the field of nuclear physics, initial ionizations as low as 1000 ion pairs were masured in a proportional counter by MADSEN[7]), who investigated the energy required to produce an ion pair by recoil atoms from Po, ThC, ThC′.

In the experiments just mentioned, as well as in others, not much attention was given to the ion calibration of the counter, i. e. to the accuracy of the energy determination, and to the resolving power, or energy resolution, of the method. It is our impression that the technique was not pressed forward until recently because of unjustified lack of confidence in the proportional counter as an accurate instrument. The development of a quantitative proportional counter technique for accurate measurements of energies in the range 100 e. v. to 50 k. e. v. (or more) was made independently in the last two years at the University of Glasgow[8]) and at the Chalk-River Laboratory[9]). As we shall see, the technique is extremely simple when considering the amount of information it yields, and may be applied to the study of beta spectra in the low energy region. With respect to the conventional β spectrometry techniques, the proportional counter technique not only brings down to about 100 e. v. the region which is possible to investigate, but also avoids windows and, in many cases, material supports, inasmuch as the radioactive substance under investigation may be placed in a gaseous form inside the counter.

Experimental Apparatus.

The apparatus, briefly, consists of a proportional counter placed in a shielded box, connected to a linear amplifier the output of which is fed into a multi-channel pulse analyser (Chalk River), or an oscilloscope provided with a camera (Glasgow) to photograph the pulses. Another possibility would be to feed the output of the linear amplifier into a single amplitude discriminator, in order to obtain an integral curve of the pulse distribution (a so-called "bias curve", giving the number of pulses as a function of the discriminator bias setting).

The Method for Sorting Pulse Amplitudes.

The single discriminator technique is extremely simple and is sufficient to recognise, for example, a mono-energetic line of electrons produced inside the counter gas[10]). However, since to cover the entire pulse distribution a great number of readings may be needed, an integral curve (as well as a differential one taken with only few channels) obviously requires much more time than the multichannel or the photographic methods. This means that, quite apart from the actual loss of time, various counter, amplifier, and discriminator instabilities will make it impossible, in practice, to use the technique for very accurate or difficult work.

As far as the two techniques used at Chalk River and Glasgow are concerned, the main advantages of the photographic method are its low cost and the fact that a permanent record of the pulse distribution is available. The main disadvantage of the photographic technique is the very long time which is required to sort out from the film, by visual measurements, the pulse size. Again a considerable advantage of the pulse analyser is the possibility of getting the results during the measurements, rather than afterwards. This permits changes of conditions (amplifier and counter gains, etc.) to be made according to the problem under investigation, without serious loss of time. Further, a not negligible advantage of the pulse analyser over the photographic method is its objectivity: while sorting pulse sizes visually from a film, it is very difficult to avoid psychological errors. As emphasised by D. West, this difficulty tends to yield pulse distribution which are pointed in appearance, i. e. tends to underestimate the width of a "peak".

Because of the longer time involved in sorting pulses in the photographic method, work with the pulse analyser having a sufficient number of channels will give, in practice, a better statistical accuracy. The pulse analyser used at Chalk River was described by Westcott and Hanna[11]). Fig. 1 and Fig. 2 illustrate some differential pulse distributions obtained at Chalk River and Glasgow, respectively with a pulse analyser and photographic method.

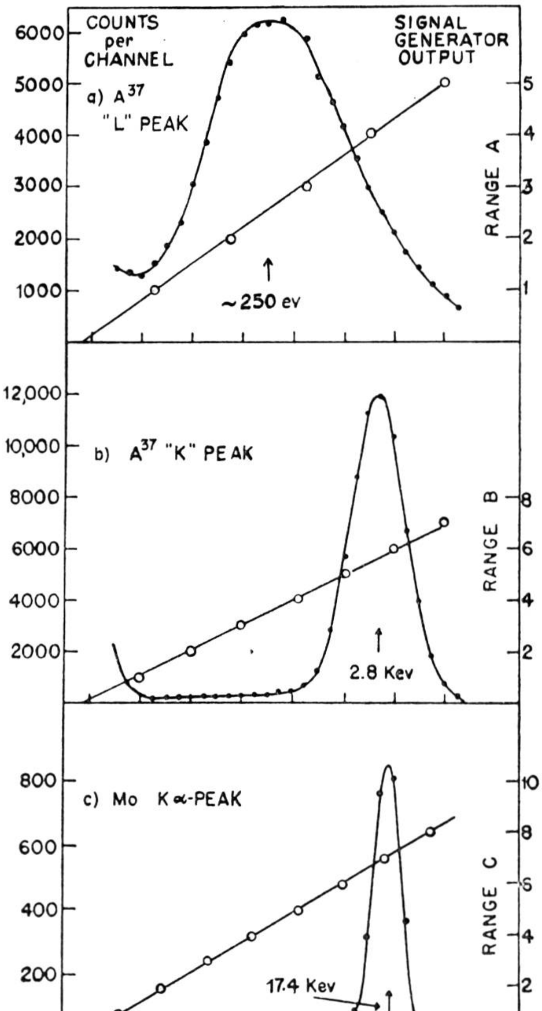

Fig. 1.

Peaks produced by ~ 250 eV, 2.8 KeV, and 17.4 KeV radiations, obtained with an electronic pulse analyser according to ref. 9. A decrease in percent width of the peaks with increasing energy is apparent. The straight lines refer to the signal generator calibration. Precise measurements of widths, however, were made using a biased amplifier to spread the 2.8 KeV and 17.4 KeV peaks over many channels of the pulse analyser. The 17.4 KeV (MoKα) radiation is obtained from a crystal spectrometer. The ~250 eV and 2.8 KeV are obtained from orbital nuclear capture A^{37}.

Counters.

Because constructional details are available in the literature[3]), we limit ourselves to few remarks and mention points concerning only the recently developed method of studying β-spectra by introducing a radioactive gas inside the counter.

The design of a proportional counter is usually less critical than the design of a GEIGER-MÜLLER counter. The homogeneity of the wire, however, is important in a proportional counter, because

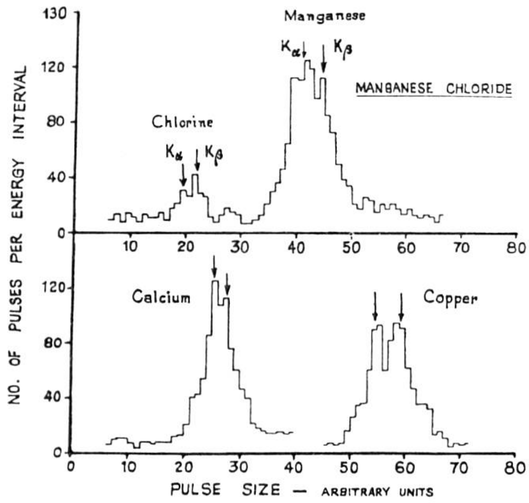

Fig. 2.

Histograms of fluorescence K X-rays obtained with the photographic methods according to ref. 8. It will be noticed that while the K_α and K_β are resolved, at least in certain cases, for calibration purposes it would be better if only one of the two lines were allowed to enter the counter.

spread in pulse size is introduced by irregularity in the wire. At HARWELL the degree of inhomogeneity of the wire is studied by examining the wire with a microscope, and in addition, by using it in a "test counter" containing A^{37}: if the distribution of pulses from the A^{37} K capture line is wider than it should be, the wire is rejected.

The counter filling, again, is not critical: in most of our experiments we have filled the counters with a noble gas (A or Xe) and CH_4, at various pressures, the proportion of CH_4 being in general not far from 20%. The presence of CH_4, as it is well known, increases the voltage for a given multiplication factor but decreases the steepness of the curve multiplication factor v. voltage; it provides, in other words, a stabilising influence. Purity of the gas is important. In Chalk River the argon and methane used were obtained from a normal tank. In HARWELL, however, the purity of the gases from normal tanks is not sufficient, and apparently purification is needed. The problem of the "purity and nature of counting gas" in chambers with and without multiplication, has been discussed in ref[2]) and in the lecture of Segré given at this congress.

As for the dimensions, counters from 2 mm. to 5 cm. in diameter and tungsten wire 0.1 mm. in diameter were used in Chalk River. In Glasgow, for the study of the spectrum of C^{14}, a counter at a pressure of 5 atmospheres of *A* and 0.5 atmosphere of N_2 was used, with a diameter of 14 cm.

When the proportional counter is used for measuring energies of beta particles by placing a radioactive gas inside the counter there

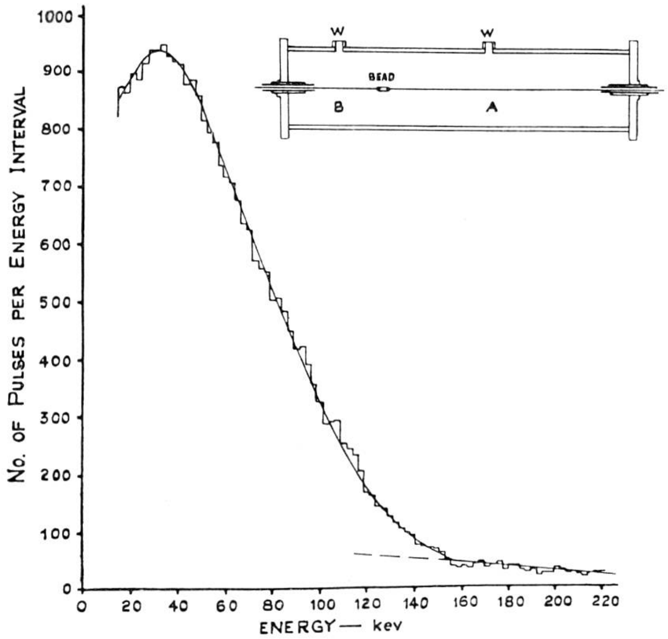

Fig. 3.

Diagram of the "split counter" according to ref. 8. The two windows *W* are for calibration of the two independent sections *A* and *B*. The curve gives a histogram of the C^{14} pulse distribution obtained in the section *A* of the counter. The correct distribution, free from end effect, is obtained by subtracting from the distribution obtained in section *A* that obtained in section *B*.

is an important source of error (end effect): at the end of the counter the weakening of the field reduces the multiplication factor, so that a fraction of the volume of the counter is associated with a "wrong multiplication factor". The counter length associated with the "wrong multiplication factor" is of the order of one counter radius, at each end, as it may be determined directly by firing a beam of α particles or X-rays in a direction perpendicular to the counter axis, at various distances from the end [1]) [7]) [8]) [9]). The end effect on a "peak", produced by a mono-energetic radiation emitted by a gas introduced inside the counter, produces a low energy "tail" rather than a spread. When dealing with electron lines (for example, in the investigation of the nuclear L capture in A^{37} [9]). this effect may not be serious, provided the ratio of the length to the radius of the counter is sufficiently high, let us say 20. However, in dealing with continuous beta spectra, the effects are usually far from negligible, especially at low energies, even with the highest length to diameter ratio which can conveniently be made. An ingenious way of solving the problem has been devised by ANGUS and collaborators[8]), who have applied it to the investigation of the beta spectrum of C^{14}. In their research the counter consisted of a cylinder of copper 75 cms. long and 14 cms. internal diameter and is shown diagrammatically in Fig. 3. The central wire consisted of two portions of different lengths held together by a little glass rod 1.5 cm. long and 1 mm. in diameter. In this way the counter is effectively divided into two independent sections, A and B, of identical "end effects", but with different wire length. If the pulse distribution is measured at each end (i. e. in each counter section) the distribution obtained by subtracting the differential curve characteristic of the short section from that characteristic of the long section, represents the distribution which would be obtained by a hypothetical counter, of length equal to the difference in length of the two sections, free from end effects. The distribution from the section A for the C^{14} spectrum is also illustrated in Fig. 3.

Electronic Problems.

We limit ourselves to some general considerations, since linear amplifiers of conventional design can usually be used. The most desirable properties of the amplifier are: (1) stability, (2) low noise, (3) lack of paralysis. Points (1) and (2) are common to most problems of nuclear physics where a linear amplifier is used. As far as noise is concerned, requirements are usually less severe than in problems where a non-amplifying ionization chamber technique is used, for example in measurements of alpha particles or proton energies*). In fact, with the large multiplication factors which it is permissible to use, the effect of the amplifier noise on the width of a line is frequently negligible. To give an example, one of our amplifiers had a peak noise equivalent to 10^4 ion pairs. At a multiplica-

*) The following discussion will be more easily understood after the section on statistical spread and on range of usable multiplication factors has been read.

tion factor of 10^4, the 2.8 kV ($\sim$ 100 initial ion pairs) K capture line in A^{37} gives a signal at the counter output of 10^6 ions, in comparison of which the noise is negligible. As for the 280 eV L_I capture line in A^{37} ($\sim$ 10 initial ion pairs), its statistical inherent width is much greater than the amplifier noise, so that the modulation by noise is very small, and one starts to count noise peaks directly even before the statistical width is appreciably increased. This is illustrated in Fig. 4.

This does not mean that one should neglect to reduce the noise: in fact, if a beta spectrum is to be investigated, the highest multipli-

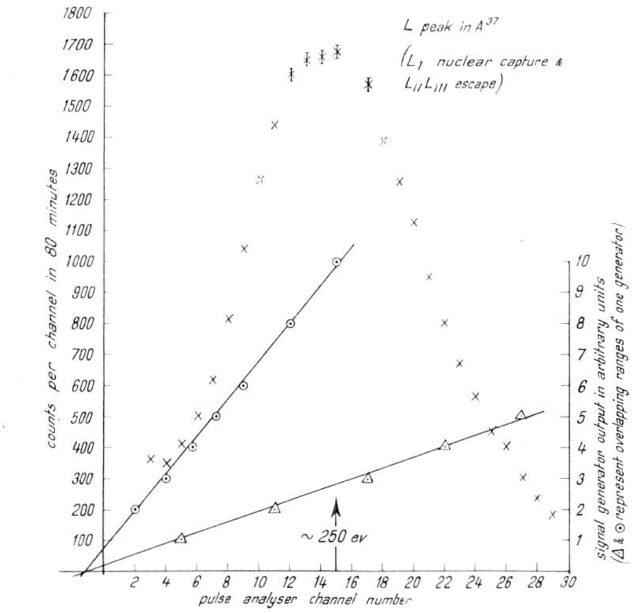

Fig. 4.

L peak from A^{37} according to ref. 9. The peak arises from the nuclear capture of L_I electrons (280 eV) and from the escape of K X-ray photons from the counter, with release of the Cl $L_{II} - L_{III}$ ionisation potential energy (200 eV). Pure nuclear capture can be observed in a counter having high stopping power for X-rays. The figure shows the direct counting of noise peaks at very low energy.

cation factor which can be used under conditions of proportionality is determined by the maximum beta ray energy, and may be well below one thousand. In this case, the investigation of the low energy part of the spectrum may present difficulties, unless the amplifier noise is kept sufficiently low.

The main emphasis on our Chalk River work was placed on the possibility of using high multiplication factors, since we had spent considerable time in studying the conditions under which such high multiplication factors can be used in the proportional region, and had experimentally shown the existence of a simple "good behaviour" criterion. (See section on range of multiplication factors.) In Glasgow the main emphasis was placed on the use of low amplifier noise (an amplifier having a peak noise as low as 1500 ion pairs was used).

The problem of avoiding paralysis is very typical of proportional counter research in beta spectroscopy. While in alpha particle work, or similar work done with non-multiplying chambers, the range of energy to be covered is usually small, investigation of beta spectra requires an enormous energy range to be investigated. This is true even in simple cases[8]) [9]) such as the investigation of the beta spectrum of H^3 and the investigation of the L capture in A^{37}. The general procedure is to use amplifier attenuation, when investigating the high energy particles. When studying the low energy part of an extended spectrum, with little or no attenuation, a large number of necessarily saturating pulses is present due to the high energy particles. Avoiding paralysis so that the distribution of small pulses is not disturbed by the presence of the saturating pulses, is the main amplifier problem. This was satisfactorily solved by G. C. HANNA, and the amplifier used will be described in a forthcoming publication[12]).

Amplifier and Pulse Analyser Calibration.

A signal generator feeds pulses of knwon size into the counter through a small capacity. In this way the "history" of the artificial pulses is the same as that of the (gas amplified) counter pulses. This is essential in accurate work, as the following information can be obtained:

(1) The amplifier noise can be measured directly, if necessary, by measuring the spread of the artificial pulses out of the amplifier.

(2) The multiplication factor can be determined in this way, since feeding artificial pulses of known size through a known capacity provides directly a "charge" calibration. This enables one to measure the charge at the output of the proportional counter (i. e. after gas amplification) and consequently the multiplication factor, since the input charge is also known provided the energy of the radiation is known. The described method would be very accurate if the artificial pulse and the counter pulse had identical shapes, or, if this is not the case, if the amplifier time constant is sufficiently long. Because differences in the rising time of artificial and counter pulses, the differentiation chops counter pulses and artificial pulses a different height, pro-

ducing uncertainties in the absolute value of the multiplication factor. However, this is not of much importance because what is of interest mainly is an approximate value of the multiplication factor, and corrections can be made when necessary.

(3) By feeding an artificial pulse before and after an experiment, it is possible to verify whether the amplifier and pulse analyser have drifted. Incidentally, similar information referring also to the counter can be obtained by making pulse analyser runs with a calibrated ionization, produced by X-rays, before and after any experiment.

(4) Usually a series of artificial pulses, of relative size accurately known, is fed into the counter, as in Figs 1 and 4.*). In this way, one can express all energy peaks in terms of signal generator output: this avoids the effects of any amplifier nonlinearity, and avoids the errors in the energy determination which would be produced by lack of accurate knowledge of bias.

(5) Expression of energy peaks in terms of signal generator, further, facilitates the use of a biased amplifier[12]) to obtain an expanded view of any part of an electron spectrum.

Ion Calibration.

The method usually adopted in the past for calibration, a polonium source, is obviously inadequate in proportional counter work at low energies.

Two calibration methods have been used at Chalk River (see also Fig. 1). First, A^{37}, a radio-isotope decaying by K capture with a period of 34.1 days, is introduced inside the counter. This provides[9]) a "calibration line" at 2800 eV, from the decay of A^{37} by K capture, and also a line at 280 eV, from the decay by capture of L_I electrons. The advantage of these calibration lines in beta ray spectroscopy is that they are truly representative of the properties of the counter as a whole, since A^{37} disintegrations are produced uniformly throughout the counter volume. For many researches A^{37} is ideal for calibration purposes: in a pile it can be obtained easily and in quantities sufficient for many calibrations ($A^{36}(n, \gamma)A^{37}$). It can be obtained in other nuclear reactions with the cyclotron[13]). Secondly, the X-ray method of calibration (extensively used by the Glasgow Group)[8]) was used. This method has the advantage of providing a practically unlimited number of calibration lines. In addition, and

*) This is usually done with the counter voltage on and with the X radiation on, in order to avoid changing conditions because of bias produced by steady currents.

contrary to A^{37}, an X-ray calibration line can be turned off and on at pleasure. The main disadvantage is that an X-ray calibration line does not give the property of the counter as a whole, being fired into a small volume in the counter. This may not be serious in applications where only a small part of the counter is used. There are several ways of using X-ray lines for calibration*) in proportional counter work:

(i) Using fluorescent radiations. This method which has been used systematically by the Glasgow Group is simple and permits to have the K_α and K_β lines fired at the same time inside the counter. It is illustrated in Fig. 2. Although we have used this method at Chalk River, for accurate calibration we have selected the following technique.

(ii) A mono-energetic beam (mainly the K_α X-radiation) from a crystal spectrometer is "fired" into the counter: although this is slightly more complicated than the fluorescence method, it gives unquestionably a better energy calibration, at least in the energy region below 30 kV. This is so because due to the unavoidable statistical widths of a line, the K_α and K_β radiations, which enter the counter in the fluorescence method, are not sufficiently well resolved for good energy calibrations. Within a small energy interval only one energy mark, the molybdenum K_α from a crystal spectrometer in most of our work, provides a better energy calibration in our opinion. In addition, the fluorescence method, in practice, gives a more intense background of white radiation.

(iii) Characteristic radiation excited at the target of the X-ray tube, in combination with filters, may give a sufficiently mono-energetic calibration.

A very ingenious idea for calibrating a proportional counter by X-rays has been proposed by T. E. Cranshaw of the Cavendish Laboratory. A pulsed X-ray tube gives a strong beam of mono-energetic radiation (let us say, photons of 17.4 kV — the molybdenum K_α). The intensity of the beam is arranged so that the probability that several photons (produced during one X-ray pulse) produce photo-electrons in the counter gas is not negligible (the amplifier time constant is fairly long). Under such conditions an analysis of the counter pulse sizes will reveal events in which one

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*) It is a pleasure to thank Drs. Hurst, Knowles and Walker for their extremely useful help in the X-ray work.

photon has interacted with the gas (17.4 kV peak), 2 photons have interacted with the gas (34.8 kV peak) etc.

When technical considerations preclude the use of an X-ray tube (for example, lack of space, or work in high mountains) a simple way of getting a calibration line is being used by D. West at Harwell: a radio-element decaying by K capture is prepared in the pile and K X-ray radiation excited under K capture provides the source. A useful source is Zn^{65} (250 days).

A supplementary remark may be useful, in connection with low energy work.

When a gas like argon or xenon is used in the counter, the number of photo-electrons liberated from the wall or window of the counter, and penetrating into the counter, is much smaller than the number of these liberated in the gas. This state of affairs is entirely different from that arising with gamma ray work, where most of the counting rate is due to the counter wall rather than to the gas. It follows that the number of spurious low energy pulses due to photo-electrons liberated from the wall is usually negligible in X-ray calibration work.

The Mean Energy necessary to produce an ion pair.

The method described for β spectroscopy requires that the mean number of ion pairs n produced by a radiation is accurately proportional to the initial energy E_i of the radiation, i. e. that the mean energy W necessary to produce an ion pair is a constant, independent of the energy. The variation of W with energy is discussed below.

A considerable amount of work has been done, mainly by measuring the ionisation current in air. Here it will be sufficient to quote the papers of Eisl[14]), Gerbes[15]) and Gray[16]), which review the results of several investigations on the energy expended per ion pair in air. The results may be summarised as follows: in air W is approximately constant for electron energies greater than 10 kV and increases for energies below 10 kV. Since energies well below 10 kV are of interest in connection with the subject of this paper, it is important to investigate further the problem. The proportional counter technique is eminently suitable for this investigation. This was done independently at Chalk River and Glasgow. The results of Curran and others[8]) on nitrogen and methane counters in the region 3 kV—25 kV show that the variation of the curve ionisation versus energy is remarkably linear in nitrogen, whereas in methane some increase in energy expenditure with decreasing energy is found*). This indicates that the increase in W for air at low energy, mentioned above, must be due to oxygen. The Glasgow Group, in addition, has investigated a mixture of argon (60 cm. Hg) plus methane (15 cm. Hg) in the electron energy range 3 kV—40 kV. Their results provide "strong evidence in favouring the view that the energy expenditure per ion pair by an electron is, for argon, very nearly constant".

We have reached the same conclusion for an $A + CH_4$ mixture and for a $Xe + CH_4$ mixture (methane represents 20—25%) in the electron range 2.8 kV—17.4 kV. More precisely we have found, for example, that the ratio of the most probable output pulse sizes produced by radiations totalling energy of 17.4 kV and 2.8 kV is $\frac{17.4}{2.8}$ within our experimental accuracy of 1.5%. In addition, our direct observation of the nuclear capture of L electrons in A^{37} permits us to draw conclusions on the behaviour of W down to initial energy of about 250 eV for $A + CH_4$ and $Xe + CH_4$ mixtures. The experiment is done by measuring the ratio of the most probable output pulse size produced by radiations totalling 2800 eV (K ionization potential of Cl) and $\sim$ 250 eV (the L ionization potential of Cl). In this case the accuracy is not as good because (1) the L peak is in fact a mixture[9]) of radiations of energy corresponding to the ionization potentials of the L_I shell and of the L_{II} and L_{III} shell, and (2) the large statistical width of the L peak prevents an accurate determination of the most probable pulse size. It can be concluded, taking the errors into account, that electrons of 280 eV produce a mean number of ion pairs greater or equal to 80% of one tenth of the mean number of ion pairs produced by 2800 eV electrons. In other words W for electrons of 200—300 V is *at most* 20% greater than W for high energy electrons. It is believed that this result on W at very low energy is the most accurate known until now. Our upper limit for W in a mixture of $A + CH_4$, combined with the statement of CURRAN and others on the increase of W in methane, proves that, at least in A or Xe, W is constant down to the lowest energies**).

In conclusion it may be stated that the fundamental requirements for the validity of the proportional counter technique in measuring energies is met, and at least in a number of gases and

*) CURRAN and collaborators[8]) state 'for methane alone an increase in energy expenditure with increasing energy was found", but in the opinion of the writer this is a misprint.

**) As pointed out by J. D. COCKCROFT, this may have application in biological problems involving radiation tolerance dosage.

over wide electron energy ranges, the number of ion pairs produced by an electron is accurately proportional to its energy. This statement should not be extended to particles different from electrons (i. e. particles of low velocity): in particular[7]) for single recoil atoms from Po, ThC, ThC^{I}, W in argon was found to be as high as 67 v. per ion pair in an energy interval of the recoils 100—170 kV.

Extension of the Technique to Beta Spectra of High Energy End Point.

We have assumed until now that the range of the electrons liberated inside the gas is small in comparison with the dimensions of the counter. In fact some particles will escape from the counter (wall effect). It may be easily shown that the fraction of spuriously low pulses (corresponding to the particles hitting the counter walls) is $R/2b$, where R is the range of particles which are supposed to be generated uniformly throughout the counter, and b is the radius of the counter. When a considerable fraction of electrons do not spend all their energy inside the counter, difficulties arise in studying beta spectra. In such a case the method is obviously unsuitable to study the energy of particles escaping from the counter, and, further, the particles escaping from the counter produce spuriously low size pulses, preventing even the low energy part of the extended spectrum to be studied. The first step in reducing the electron escape is fairly obvious: increase the dimension of the counter and or gas pressure. Rossi and Staub[1]) have used (for purposes which are different from the one discussed here, however) proportional counters at a pressure of several atmospheres. In the study of the beta spectrum of C^{14}, as mentioned above, Angus and collaborators[8]) have used a large counter filled at more than 5 atmospheres. It should be noticed that with a counter with a high ratio of diameter to length the device of the "split counter" (Fig. 3) is essential.

Another step in reducing the escape is being studied at Harwell at present. The idea is to curve the particles in a strong magnetic field in order to prevent their escape, more precisely, in order to increase their path in the gas. In a homogeneous magnetic field a particle with velocity parallel to the field is not affected by the field. However, if one is interested in studying the low energy part of an extended spectrum, what is required is that the number of spuriously low energy pulses, which are due to escape, is small compared with the number of genuine low energy pulses due to low energy electrons. A homogeneous field parallel to the counter axis can serve the purpose. For this, however, it is essential that the counter behaviour is not disturbed by the field. Rothwell and

West have studied this problem by measuring the pulse size distributions in a proportional counter placed in a strong magnetic field, in conditions such that a magnetic field does not change at all the escape probability. This condition is verified when alpha particles are fired into the counter, and also when A^{37} is introduced inside the counter (in the last case the range of the electron is completely negligible in comparison with the counter dimensions and consequently the average escape probability is practically zero, i. e. unaffected by the field). Fig. 5 shows results obtained with a counter

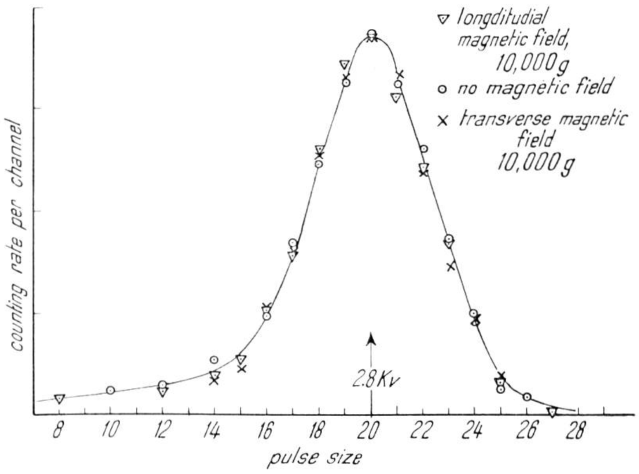

Fig. 5.

Behaviour of proportional counter containing A^{37} in strong magnetic field according to P. Rothwell and D. West. Clearly the counter characteristic is not adversely affected by strong magnetic fields.

with $A + CH_4$ plus traces of A^{37} filling, with and without a 10,000 gauss homogeneous field parallel or normal to the counter wire. The identity of the differential pulse size distributions in the three cases proves conclusively that the counter is completely unaffected by the field, i. e. that from an instrumental point of view the method suggested is operative. Although this might have been expected, on account of the small free path of electrons drifting to the wire, the results are gratifying in view of possible applications of the technique. When a radioactive gas, emitting high energy electrons, is introduced in the counter, on the other hand, a considerable increase of the number of large size pulses was observed, as expected.

Another possibility for studying the low energy part of an extended spectrum is the (anti-coincidence) technique of rejecting pulses corresponding to particles having escaped from the proportional counter. This is being considered at present at Harwell.

Spread in Pulse Size (Trivial Causes).

Even if a mono-energetic radiation is absorbed in the counter, there would be some spread in the counter pulse amplitudes. Trivial causes of spread are:—

1. Instability of the multiplication factor during an experiment. Generally, the drift of the multiplication factor M was found to be quite small even in runs lasting more than one hour. M varies approximately exponentially with the voltage, and modern stabilised H. T. supplies are sufficiently stable: by this we mean that the drift due to change in voltage can be made smaller*) than the spread due to fundamental causes. In one of our typical counters M varied by a factor 2 for a change of voltage of 80 volts.
2. Drift in amplifier and pulse analyser. It would be out of place to discuss here the general problem of stability. The drift in the counter *and* electronic equipment, as a whole, can be measured by a calibrating X-ray line.
3. Spread due to imperfect electron collection and in general to gas impurities. Although this may be very serious, the problem, wich has been discussed in reference (2), is soluble.
4. Inhomogeneities in the wire counter. Careful selection of the wire is recommended.
5. Amplifier noise. It has already been stated that in a proportional counter this cause of spread is frequently negligible.

When careful attention is paid to the above-mentioned causes it may be stated that, when the energy is below 40 kV, the spread produced by them can be kept definitely below the spread produced by the fluctuations in the initial number of ionizations and fluctuations introduced by the statistics of the multiplication process in the counter, which are discussed below.

Statistical Spread.

The first point we have investigated at Chalk River was the dependence of the spread upon the multiplication factor. We have found that the width of a peak expressed in percent of the energy is in fact independent of the gas multiplication factor over an enormous range. More precisely, the "constant width" range extends from the low values of M, at which the peak under investigation still

*) This is only true, however, provided that the radiation being investigated has a fairly small energy, let us say, less than 40 kV.

stands well above the amplifier noise, to values of M where lack of gas proportionality, due to space charge effects, is measurable. We will discuss in the next section the practical and theoretical significance of this critical value of the multiplication factor, function of the initial ionization, at which both increase in width and lack of linearity start to appear. Here, when referring to the width and shape of a peak, it is intended to refer to these in the region of "constant width". In a typical counter, for example, the width of the 2.8 KeV A^{37} line was found to be constant for voltages ranging from 2100 to 2900 volts.

Correcting for the low energy tail, the shape of the peaks produced by the 17.4 and 2.8 kV radiations was found to be Gaussian, at least

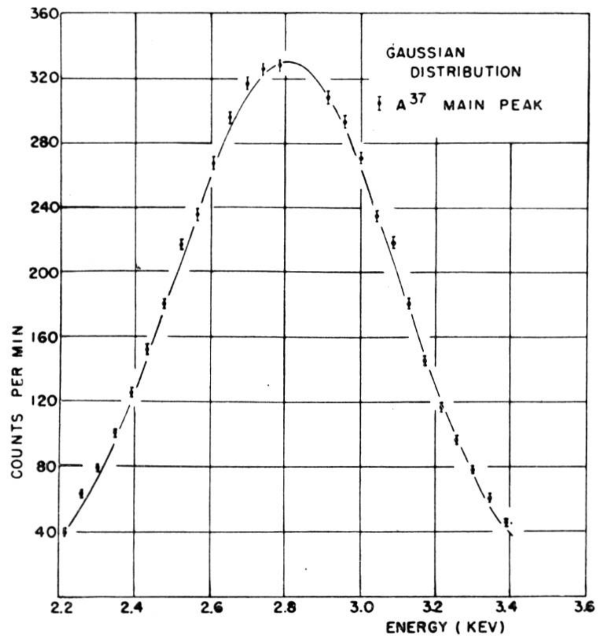

Fig. 6.
GAUSSIAN distribution of the A^{37} K capture peak.

over the energy range ($\pm$ 3 standard deviations) where background fluctuations do not disturb the measurements. Fig. 6, for example, indicates the Gaussian character of the A^{37} peak, which in this run was spread over all the channels.

Since the spread is due not only to statistical fluctuations but also to trivial causes, it cannot be concluded that the "ideal" peaks (i. e. peaks with the spread due to statistical causes only) would be Gaussian. However, for the counter of which we give data — one of our counters giving the least spread — we have reasons to believe that the "trivial" spread is fairly small in comparison with the statistical spread*). Anyway the observed values of the standard deviation of the pulse size obtained by fitting the experimental points to a Gauss distribution will give an upper limit to the standard deviation of the corresponding "ideal peak". Table I summarises the results.

Table I.

Radiation energy (ev) E_i	Estimated mean number of ion pairs released by radiation, n	Observed standard deviation (% of pulse size)
17,400	700	$(4.0 \pm 0.2)\%$
2,800	110	$\left(8.8 \begin{cases} +0.3 \\ -0.1 \end{cases}\right)\%$
$\sim$ 250	$\sim$10	$(36 \pm 4)\%$

It is seen that the observed standard deviation, measured in percent of pulse size (a convenient quantity to express the spread of a peak) for radiations of 17,400, 2800, $\sim$ 250 eV is not very different from $\pm \sqrt{n}/n$, n being the mean initial number of ion pairs released by these radiations. It is interesting to compare these results with published theories. A theoretical analysis of the fluctuations of the initial number of ionisations produced when a radiation is completely absorbed in the gas was given by FANO[17]). This author estimates that the mean square deviation of the number of ionisations is substantially smaller than that governed by a Poisson distribution (which would be n) and may be of the order of n/K with K between 2 and 3. To this variance one has to add the variance introduced by the statistics of the multiplication process in the counter, which was discussed by SNYDER and by FRISCH[18]), and found to be equal to n. Consequently the theory predicts a mean square deviation at the output of the proportional counter, referred back to the initial number of ions, n, equal to $n/K + n$.

This value is considerably higher than the observed value, even if K were to be higher than the value predicted by FANO. Since K is unlikely to be very great, and in any case the observed values are upper limits for the mean square deviation, our results show definitely that the gas amplification introduces less spread than the theory would predict. As emphasised by G. C. HANNA, the reason of the discrepancy between our experiments and the theory

*) The fact that the standard deviation is approximately proportional to the square root of the input energy is best indication of the validity of the statement.

is probably the over-simplification of the starting assumptions of the theory.

To evaluate the variance introduced in the counter multiplication process, in fact, FRISCH[18]) assumes that the probability for an electron, drifting to the wire, to produce an ion pair in the gas is solely a function of the electric field, i. e. solely a function of its distance from the wire. Actually the probability must depend upon the previous history of the electron, because an electron having just produced an ion pair must be accelerated again, no matter what its distance from the wire is. This produces a compensating effect probably responsible for the discrepancy between theory and experiment.

From a practical point of view, the discrepancy is gratifying, in as much the energy resolution of the method, observed experimentally, is better than had been expected.

The useful range of gas multiplication.

The range of useful multiplication factors was studied carefully by

(1) measuring the widths of the 2.8 KeV and of the 17.4 KeV peaks as a function of the voltage;

(2) measuring the ratio of the most probable outpout pulse sizes produced by the 2.8 KeV and the 17.4 KeV radiations, as a function of the voltage.

The linearity of the gas multiplication was established within the experimental accuracy of 1.5%, over a range extending from the lowest value at which careful width measurements could be made ($M \approx 300$) to a fairly critical value, M_c, where lack of linearity is easily detected. The critical value M_c is a function of the radiation energy E_i being greater the smaller E_i. As mentioned above, when the multiplication factor is close to $M_c(E_i)$, the width of the peak corresponding to the energy E_i increases in an easily detectable way. All these facts strongly suggest that proportionality and correct peak width are maintained up to that multiplication factor which produces a certain total output pulse, that is $E_i \times M_c(E_i) =$ constant. In a typical counter the constant was about 3×10^8 eV. It follows that for low energy measurements correspondingly large multiplication factors may be used. In practice a quick criterion to verify that the range of voltage is satisfactory is to inspect on an oscilloscope the spread of the peak produced by the most energetic radiation under investigation: the maximum voltage which can be used must be, let us say, 50 volts below the voltage at which an increase in percentage width is plainly observable.

We want to discuss now the observed "good behaviour criterion", i. e. $E_i \times M$ must be smaller than about 10^8 e. v.*). The existence of a fairly critical output pulse must correspond to a total charge which is not negligible in comparison with the pre-existing charge at the wire — which is of the order of 10^9 electron charges per cm. Now the relation $E_i \times M < 10^8$ e. v. means that the charge after gas amplification must be less than $10^8/25 = 4 \times 10^6$ electron charges. If the electron of an avalanche diffuse over about 1 mm, it is seen that the "critical pulse" corresponds to about 4% of the pre-existing charge.

Conclusions.

In conclusion it may be useful to list here the problems for the investigation of which the described technique of the proportional counter, used at high multiplication with careful ion calibration, is eminently suitable.

(1) Investigations of beta spectra of radio-elements, of low end point energy, which may be introduced in gaseous form into the counter (e. g. H^3, C^{14})[8])[9]).

(2) Investigation of the low energy part of the beta spectrum extending to energies of about 1 MeV. This is being done at the present at Harwell, by Rothwell and West (magnetic fields).

(3) Investigation of beta spectra of very weak intensity. The high solid angle of a counter makes possible this application.

(4) Investigation of orbital electron capture. Nuclear capture of L_I electrons was first observed by this technique[9]).

(5) Isomeric transitions and low energy gamma rays. Study of X-ray emission in nuclear problems. As an example we quote the study of the Ra-D radiations[8]).

(6) X-ray applications. In every problem of X-ray research where the intensity is weak and a Geiger counter was used until now as a detector, it is clear that the use of a proportional counter will reduce background by giving supplementary information on another parameter, the energy of the X-ray quantum.

(7) Fluorescence X-ray analysis. This was initiated by Knowles and Walker at Chalk River.

*) The condition is certainly less stringent than this when the original ionisation is spread over a large distance.

(8) Cosmic Ray work. Measurements of the specific ionisation in a proportional counter can be used in the investigation of mass spectra of intermediate particles, when the magnetic rigidity is measured at the same time.

(9) Study of the specific ionisation as a function of the energy of a particle. According to a kind communication of Professor DEE, this problem is being investigated in his laboratory.

(10) Study of fluctuation of ionisation[9]).

(11) Study of the change of the mean energy W spent in producing an ion pair as a function of the energy[8])[9]). An absolute determination of W in various gases can also be made.

(12) In some cases the proportional counter technique can reduce the effective background when counting extremely weak intensities of a radio-element. For example, in an attempt to detect free neutrinos, it was proposed[19]) to irradiate a large mass of Chlorine, and to measure A^{37} produced in the reaction Cl^{37} + neutrino → A^{37} + electron. Clearly, if one measure the pulse size distribution in a proportional counter, the effective background of the counter is greatly reduced due to the narrow width of the A^{37} peak. In this way a counter having an effective background as low as one count in several hours has been obtained.

(13) In some problems such as the exploration of the neutron density in a pile, it may be useful to detect neutrons at considerable distances from electronic equipment. For this purpose proportional counters (BF_4, CH_4 filled, B or U coated counters) have been used at Chalk River and Harwell: in these counters the (positive) H. T. voltage was connected to the wire by a cable, having a length of the order of 100 ft. The counter case was grounded and the first tube of the amplifier (about 100 ft. from the counter) was insulated from the wire by a condenser.

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