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Local space charge effect in conventional avalanche counters at moderate specific ionization

Jan Sernicki

Abstract The purpose of this investigation is the determination of a simple criterion of local space charge effect in conventional avalanche counters at moderate specific ionization. Parallel-plate avalanche counters (PPAC) with an electrode spacing d from 0.1 to 0.4 cm have been used to register low-energy alpha particles at n-heptane vapour pressures of p ≥ 5 Torr. The criterion determined is a simple h/p^m function describing the variability of the product of effective gas amplification and actual particle energy loss, where both the numerical h coefficient and the exponent m assume different values for the various values of d. The product variability at higher gas pressures in PPAC detector – having regard to practical side of criterion determined – can be relatively well described by a single linear function. The results obtained are discussed from their veracity point of view.

Key words avalanche counter • gas amplification • n-heptane vapour • pulse amplitude characteristic • space charge

Introduction

When the radiation initiating the discharge growth within detector interelectrode gas space generates a sufficiently large number of charge carriers during primary ionization process, then the carrier multiplication process in a strong electric field, i.e. the gas gain process, will be obstructed by local space charge effect. The created charges cause a dynamic deformation of electric field distribution. In consequence, a non-self-sustained discharge develops at the first Townsend coefficient values (the coefficient determining, for one charge carrier, the number of ionization events per unit path length in the field direction) being different from the value resulting from the voltage applied to electrodes. This effect manifests itself on the pulse amplitude ($\overline{U}_{exp}$) characteristics and gas gain ($\overline{M}$) characteristics examined in the semilogarithmic coordinate system as the section of their nonlinear variability. Corresponding to the lower bound of voltages assigned to this section is certain critical value of effective gas amplification, above which in reality the effect of space charges is generally to be expected. Hence, the product of the critical absolute value of gas amplification ($\overline{M}_{abs}$) and the energy lost in detector (ΔE) by the radiation detected, in practice plays the role of a criterion of the effect occurrence. The effective value of the $\overline{M}_{abs} \times \Delta E$ product is undoubtedly dependent upon the most comprehensively understood measurement conditions.

The space charge effect has also been observed in avalanche counters [1, 5–7, 9, 11–14, 21] but as yet, no solutions have been found for them, as there have been – in form of simple useful criteria of $\overline{M}_{abs} \times \Delta E$ product type – presented in the old-time papers concerning proportional counters [3, 4].

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The determination of the criterion of space charge effect in avalanche counters reduces to numerical formulation of the above product which can be written in somewhat other form:

$$(1) \quad \overline{M}_{abs} \times \Delta E = \overline{M}_{abs} \times (dE/dx)_d = \overline{M}_{abs} \times dE/dx \times d$$

where dE/dx is the specific particle energy loss (stopping power), and d refers to the electrode spacing. It can be assumed that the stopping power – for a given species of detected particles – is only an explicit function of pressure, i.e. dE/dx = H×p, where H stands for the respective proportionality factor. It should be noted that equation (1) is valid with the following assumptions:

- the particles pass the counter perpendicularly to its electrodes;
- the charge density resulting from the primary ionization process (specific ionization) is constant within entire interelectrode space of the counter, i.e. (dE/dx)/W = const., where W denotes the ionization work.

Then, the need to express $\overline{M}_{abs}$ from equation (1) through experimental quantities still requires the counter pulse amplitudes ($\overline{U}_{exp}$) to be proportional to the total number (n_{exp}) of the charge carriers collected at the counter anode during the detection of a single particle. Hence the additional stipulations for practical accomplishment of the investigation:

- the amplifying circuitry time constant should be as large as it is required by the operation with ionic component of the signal generated at the counter output; therefore, the intensity of detected particles should be relatively small;
- the electronic measuring system should be completely linear.

The purpose of the author's investigation is the determination of a simple criterion of local space charge effect in conventional avalanche counters at moderate specific ionization. Parallel-plate avalanche counters (PPAC) with different electrode spacing d have been used to register low-energy alpha particles at different n-heptane vapour pressures p. The investigation has been performed under measurement conditions being generally typical for the majority of physical experiments in which the PPAC detectors are used.

Test setup

The measurements of the pulse amplitude characteristics of avalanche counters filled with n-heptane vapour were carried out in an experimental arrangement with an ^{241}Am source of moderate activity [14, 16–18]; the divergence (θ) of radiated alpha particles beam did not exceed 8° (see Fig. 1). A transmission PPAC with replaceable aluminized mylar foil electrode sets having electrode spacings d of 1, 2, 3 and 4 mm was used [14, 15]. The experimental arrangement operated at n-heptane pressures p from 5 to 30 Torr. Fig. 2 shows, for the above measurement conditions, the variability of the actual energy of alpha particles and the corresponding variability of the particle energy loss within the PPAC interelectrode gap *vs.* gas pressure changes within the experimental arrangement. The particle energy losses in the gas have been evaluated basing upon the data taken from ref. [20], while the losses in the front electrode have been evaluated using the tables from ref. [10].

The PPAC detector operated in conjunction with a conventional charge-sensitive preamplifier having slow energetic output [14,

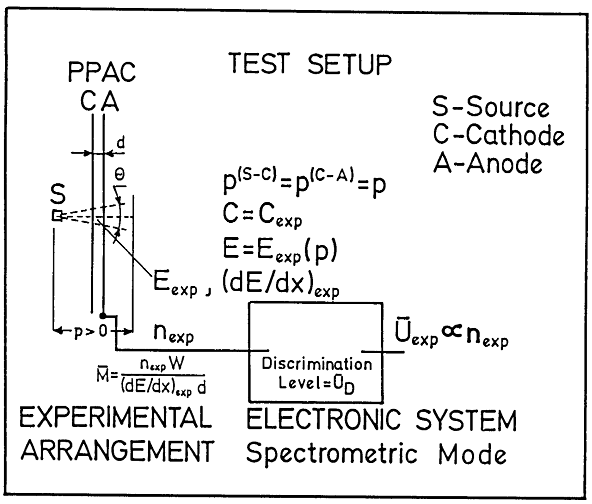

Fig. 1. Conception of investigation realization and actual test setup operating conditions. The n_{exp} and the $\overline{U}_{exp}$ symbols refer to the total number of charge carriers collected at PPAC anode in response to a single particle, and to the amplitude of the recorded pulse, respectively. See ref. [15] for data on the C_{exp} cathodes of the PPAC. The remaining symbols are depicted in the text.

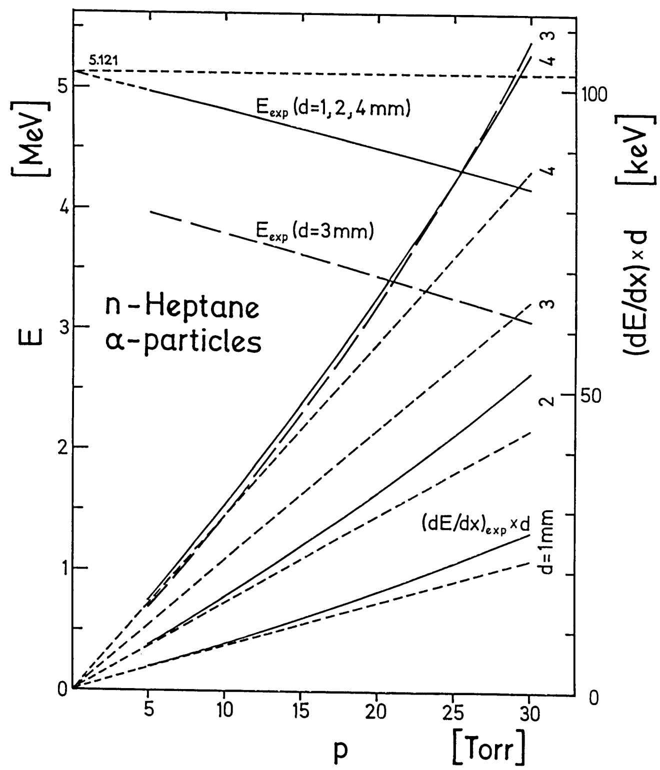

Fig. 2. Mean effective energy E of alpha particles and its corresponding particle energy loss in the PPAC interelectrode gas space, determined for actual measurement conditions. Under these conditions (see Fig. 1) p represents the n-heptane vapour pressure. The plots apply to those alpha particles which follow paths perpendicular to the counter electrodes.

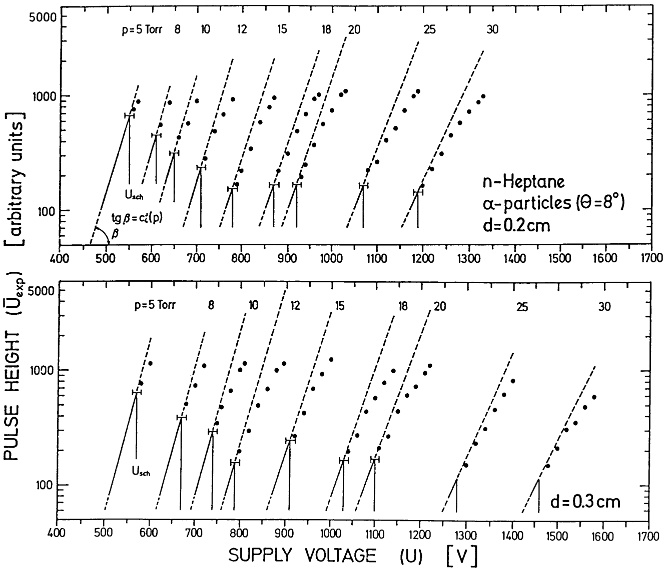

Fig. 3. Nonlinear sections of PPAC pulse amplitude characteristics plotted in the semilogarithmic coordinate system. Below U_{sch} voltages determining the lower limits of these sections, each characteristic features a linear course with $\partial\overline{U}_{exp}/\partial U$ slope depending upon p pressure value (see ref. [18]). The accuracy of the U_{sch} voltages does not exceed ± 10 V.

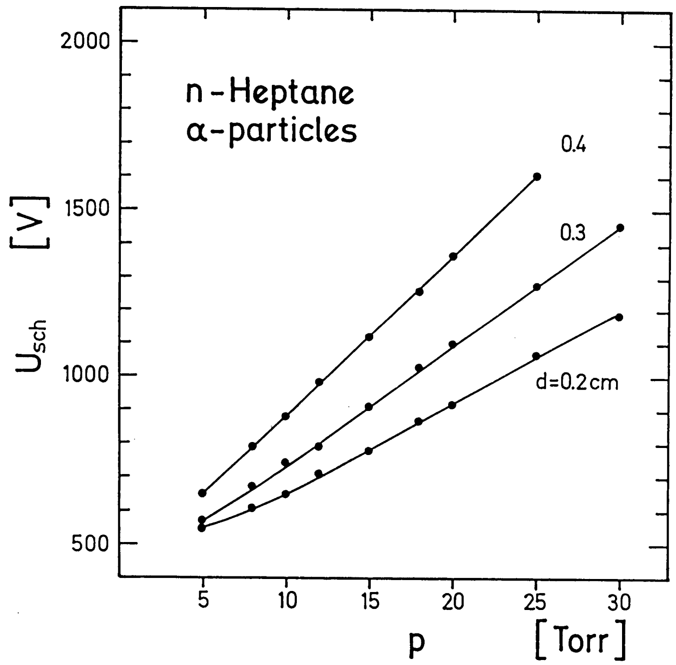

Fig. 4. Lower bounds (U_{sch}) of voltages corresponding to nonlinear sections of log $\overline{U}_{exp}=\xi(U)$ characteristics under assumed measurement conditions (see Figs. 1, 2 and 3).

15] and with a spectrometric amplifier the output signal of which controlled a multichannel pulse amplitude analyzer. The amplifying circuitry provided time constans of the order of microseconds. The satisfactory energy resolution of the test setup [14] provided for a very precise localization of the peak ($\overline{U}_{exp}$) of the PPAC pulse amplitude distribution being recorded.

The test setup allowed the accomplishment of investigation at PPAC operating voltages belonging to the sets of applicable operating conditions of conventional avalanche counters [18, 19].

Results

PPAC pulse amplitude characteristics *vs.* supply voltage

The experimental pulse amplitude ($\overline{U}_{exp}$) characteristics as a function of the voltage supplying PPAC for various values of gas pressure have been determined for all PPAC electrode sets depicted in Section: "Test setup". After having plotted the $\overline{U}_{exp} = f(U)$ characteristics in the semilogarithmic coordinate system, it was found that, except for the characteristics of PPAC having d = 0.1 cm (with the pressure varied from 5 to 18 Torr), all the remaining characteristics – as expected (see ref. [14]) - have their nonlinear variability section in their end part (Fig. 3 shows the results for d = 0.2 and 0.3 cm). The lower bound (U_{sch}) of the voltages corresponding to this section is conditioned by the beginning of space charge effect in PPAC.

It is worth noting that the advantage of the above mentioned characteristics is that they are not burdened with any additional errors usually resulting from additional transformations of primary characteristics.

Lower bounds of voltages corresponding to space charge effect in PPACs

By numerically analyzing the experimental log $\overline{U}_{exp} = \xi(U)$ characteristics of the PPAC detectors, lower bounds have been determined for the voltages corresponding to the sections of space charge effect under the measurement conditions being assumed (Fig. 4). The curves presented correspond exactly to this moderate specific ionization in n-heptane.

Variability of critical pulse amplitudes vs. pressure

The analyzed pulse amplitude characteristics are, at the same time, the characteristics of the product of arbitrary gas amplification value and actual particle energy loss in the PPAC interelectrode gap. It is interesting to see how the $\overline{M}_{arb} \times (dE/dx)_d = \overline{U}_{exp}$ product varies with pressure, at the voltages determining the beginning of space charge effect under assumed measurement conditions. This is shown in Fig. 5. Thus, it can be inferred from this Figure that the criterion of the PPAC space charge effect must be a gas pressure function. On the other hand, the variability type itself indicates that the variability can be approximated by some elementary function.

According to the stipulation hinted at the beginning, in order to make use of the functions featuring the most simple analytic notation possible, the h/p^m function has been chosen from among elementary functions, this function satisfactorily approximating the points of Fig. 5 for individual d values. Thus, the product of gas amplification and actual particle energy loss is, in general, equal to h/p^m, where the exponent m assumes the values 1.05 and 1.06 and 0.81 for d=0.2 and 0.3 and 0.4 cm, respectively; the symbol h denotes the numerical coefficient of this function. So, the final criteria of the space charge effect in PPAC detectors will be functions of this type.

Criteria of space charge effect in PPACs

To determine the values of h coefficient in the functions from Section: "Variability of critical pulse amplitudes *vs.* pressure", these functions now approximating the $\overline{M}_{abs} \times (dE/dx)_d$ points, the critical absolute values ($\overline{M}_{abs}$) of PPAC gas amplification should be calculated. These absolute gas amplification values (see Appendix) have been calculated for the voltages determining the beginning of space charge effect in the detector (U_{sch} voltages from Fig. 4). The $\overline{M}_{abs} \times (dE/dx)_d$ product values obtained are presented in Fig. 6. The points shown in the Figure are approximated by the three functions depicted in Table 1. These three relations are, thereby, the criteria of space charge effect in PPACs. To make the use of them easier, the Appendix also gives general equations for absolute gas gain characteristics (without space charge effect), the equations being valid for PPAC detector filled with n-heptane vapour. The characteristics represent all experimental curves of arbitrary gas amplification.

Observing the distribution of $\overline{M}_{abs} \times (dE/dx)_d$ points in Fig. 6, it can be noticed that with the pressure increase, both the dependence of these points on p weakened and their mutual spacing was reduced. Thus, it seems to be reasonable – from the practical point of view – to replace all these points, at appropriately higher pressures, by a single approximating function of ap+b type, the positioning of which can also be seen in Fig. 6. Thereby a slightly limited but considerably simpler criterion, expressed in [keV] units, has been obtained:

(2) $(\overline{M}_{abs} \times (dE/dx)_d)_c = (-3.65[keV/Torr] \times p + 366[keV]) \times 10^3$

which – to a quite satisfactory extent – is valid for the following n-heptane vapour pressures in turn:
$p \geq 12.8$ Torr for $d = 0.2$ cm; $p \geq 11.6$ Torr for $d = 0.3$ cm; $p \geq 9.4$ Torr for $d = 0.4$ cm.

The writing-down of the relation (2) confirms once more that, irrespective of the extent of simplification introduced, the practical criterion of the effect of space charges in avalanche counters remains a function of gas pressure.

Discussion

Veracity of variability of product value of PPAC gas amplification and actual particle energy loss

Figs. 5 and 6 clearly show that the $\overline{M} \times (dE/dx)_d$ product values, where $\overline{M}$ denotes generally the PPAC gas amplification, and $(dE/dx)_d$ refers to the actual particle energy loss in the detector interelectrode gap, are the functions of both the gas pressure (p) and the size of distance between the electrodes (d). Though, the dependence of this product on these two quantities decidedly weakens at higher pressures. Nevertheless, the linear approximation of measuring points at higher pressures does not correspond to a constant function. Hence the conclusion that the value of $\overline{M} \times (dE/dx)_d$ product should be recognized as a value varying over the entire range of n-heptane pressures commonly used in conventional avalanche counters.

The development of gas gain process – with primary ionization path being perpendicular to the counter electrode set – may be accompanied by a certain dynamic change in electric field distribution in the interelectrode gap. The change in electric field should influence, first of all, the electrons from the vicinity of the

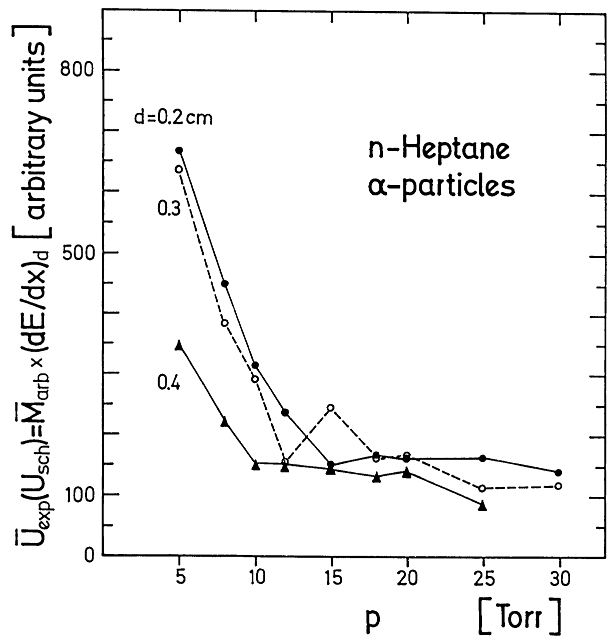

Fig. 5. Variability of critical pulse amplitudes – for the voltages determining the beginning of PPAC space charge effect under assumed measurement conditions (see Fig. 4) – as a function of gas pressure. $\overline{M}_{arb}$ denotes the arbitrary detector gas amplification, while $(dE/dx)_d$ is the actual particle energy loss within the interelectrode space.

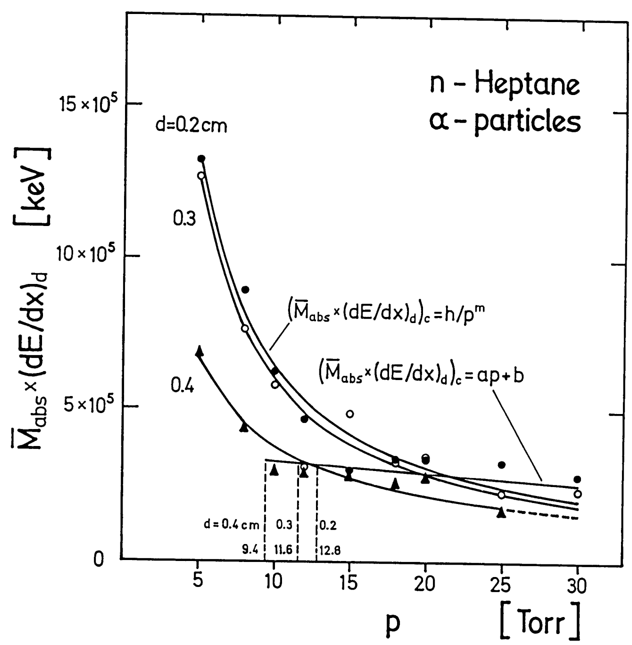

Fig. 6. Variability of the product of the critical absolute PPAC gas amplification value (for the voltages determining the beginning of space charge effect) and the actual loss of particle energy within the detector interelectrode space.

Table 1. Product of critical absolute value of gas amplification ($\overline{M}_{abs}$) and actual praticle energy loss $(dE/dx)_d$, as a criterion of space charge effect in a PPAC detector having an electrode spacing equal to d at a given p value. The pressure p is expressed in Torrs.

d [cm]	$(\overline{M}_{abs} \times (dE/dx)_d)_c$ [keV]
0.2	$7.193 \times 10^6/p^{1.05}$
0.3	$6.817 \times 10^6/p^{1.06}$
0.4	$2.443 \times 10^6/p^{0.81}$

cathode, as the actual field may be in fact the consequence of screening effects initiated by the charge column being present in the gap [2, 5]. In turn, the spread of this column in radial direction (this takes place in the gas gain process) is undoubtedly the function of the pd product [8]. The consequence of all these phenomena may be just the observed variability of $\overline{M} \times (dE/dx)_d$ product value at lower pressures of n-heptane vapour.

Then, at higher pressures, the processes of charge carrier regeneration grow in effectiveness (see ref. [15]). The processes should, doubtlessly, also change the spatial charge distribution in the interelectrode gap more and more effectively. The dynamics of exactly these phenomena may be responsible for such a behaviour of the product concerned, as is shown (for the pressure range) in Figs. 5 and 6.

Veracity of absolute PPAC gas amplification values

It is strongly desirable, from the practical point of view, to know the maximum spread percentage of absolute values of gas amplification corresponding to both the measuring points ($\overline{M}_{abs}$) in Fig. 6 and the general equations for $(\overline{M}_{abs})_g$ characteristics, in relation to the gas amplification resulting from the determined criterion $(\overline{M}_{abs})_c$ of the space charge effect in PPAC. Because, the actual value of this spread is a measure of veracity of not only the absolute gas amplification values themselves but also of the whole criterion.

Spread of values of gas amplification – corresponding to measuring points – vs. the amplification resulting from PPAC space charge effect criterion

The numerically determined rational functions $\overline{M} \times (dE/dx)_d)_c = \zeta(p)$ satisfactorily approximate the measuring points of Figs. 5 and 6. The root of mean square spread of $\overline{M}_{abs} \times (dE/dx)_d$ points of Fig. 6 amounts to 65.2×10^3, 73.8×10^3 and 39.4×10^3 keV for d = 0.2, 0.3 and 0.4 cm, respectively. Instead, the highest maximum difference between the values of analyzed quantities, as related to the corresponding criterion curve, does not exceed 39%. This value characterizes, at the same time, the veracity of gas amplification values themselves, both $\overline{M}_{abs}$ and $\overline{M}_{arb}$, corresponding to the measuring points.

Also, the numerically determined resultant linear function $(\overline{M} \times (dE/dx)_d)_c = \varphi(p)$ satisfactorily approximates, at pressures generally ≥ 9.4 Torr (see Section: "Criteria of space charge effect in PPACs"), appropriately chosen measuring points in Figs. 5 and 6. Now, the root of mean square spread of the $\overline{M}_{abs} \times (dE/dx)_d$ amounts to 26.4×10^3 keV. Then, the highest maximum of the difference between the values of analyzed quantities, as related to the criterion straight line – neglecting only the point for p = 15 Torr and d = 0.3 cm – does not exceed 37%.

The above analysis convinces that, after all, the criterion of space charge effect in PPAC detectors – even for higher p values – is not a "const" type function. So, this means that the beginning of this effect in avalanche counters is generally a function of pressure.

Spread of gas amplification values – corresponding to general characteristic equations – vs. the amplification resulting from PPAC space charge effect criterion

The spreads of $(\overline{M}_{abs})_g \times (dE/dx)_d$ have been analyzed, where $(\overline{M}_{abs})_g$ is determined by the general equations for gas gain characteristics included in Table 2, in relation to $(\overline{M}_{abs} \times (dE/dx)_d)_c$ values derived from determined criterion of PPAC space charge effect (see Table 1). The highest maximum of the difference between the values of analyzed quantities reaches 58%. This value, which at the same time characterizes the $(\overline{M}_{abs})_g$ quantity itself, is slightly higher than the value given in the previous Section (39%).

In turn, the highest maximum of the diffrence between the values of $(\overline{M}_{abs})_g \times (dE/dx)_d$ and $(\overline{M}_{abs} \times (dE/dx)_d)_c$ products, as related to these latter values derived from the linear criterion (see Fig. 6), does not exceed 61% except for the case of p = 12.8 Torr and d = 0.2 cm. This value is higher than that given in Section: "Spread of values of gas amplification – corresponding to meas-

d [cm]	$(\overline{M}_{abs})_g = c_0 \exp(c_4U + c)$	p [Torr]
0.1	$39.8 \exp(-0.97p+0.0172U+0.001712pU+0.0192p^2-0.000062p^2U)$	5 – 18
0.2	$1.22 \exp(-1.19p+0.0283U+0.000791pU+0.0206p^2-0.000049p^2U)$	< 10
	$1.22 \exp(-1.19p+0.0363U-0.000493pU+0.0206p^2)$	≥ 10
0.3	$0.0410 \exp(-1.36p+0.0396U-0.000717pU+0.0278p^2)$	5 – 30
0.4	$0.00528 \exp(-1.50p+0.0386U-0.000952pU+0.0417p^2)$	5 – 30

Table 2. General equations of the characteristics of PPAC absolute gas amplification $(\overline{M}_{abs})_g$. These are valid within given ranges of n-heptane pressures (p). U is expressed in Volts. The coefficient c_0 has a constant value for given electrode spacing (d), while the coefficients c_4 and c are functions of p.

uring points – *vs*. the amplification resulting from PPAC space charge effect criterion" (37%).

However, in view of satisfactory approximations – by means of elementary functions – of both coefficients in relation (3) (see Appendix), the general equations for PPAC gas gain characteristics – given in Table 2 – can be considered as sufficiently veracious.

Conclusions

The practical criteria of the PPAC spatial charge effect, at moderate specific ionization, have been successfully determined using only elementary functions in calculation process. These criteria are relatively simple analytic representations of the product of effective gas amplification and actual particle energy loss, but they are different for individual electrode spacing values (d) in a given PPAC detector.

The determined product values are subject to change over the entire n-heptane vapour pressure (p) range commonly used in conventional avalanche counters. Probably the spatial distribution of charges generated in primary ionization process, which implies some subtle phenomena (screening effect) accompanying the transfer of the charges over the interelectrode gap (at relatively low pd values), is decisive in this change as well as the more and more efective – at higher pressures – charge carrier regeneration processes. In general, all these phenomena dynamically change the spatial distribution of global charge in the interelectrode gap.

It should be fully realized that the critical gas amplification values at which the effect of spatial charge in PPAC starts to appear are in every case the effective values which, as a matter of fact, characterize a given experimental arrangement.

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Appendix

General equations for absolute gas gain characteristics of PPAC detectors filled with n-heptane vapour

The calculation of the mean value of PPAC detector absolute gas amplification (see ref. [18]) by use of the relation $\overline{M}_{abs} = [\exp(\alpha d)-1]/\alpha d$, and additionally, of the general $(\alpha/p)_g$ equation being the numerically determined Townsend formula, in which α denotes the first Townsend coefficient, is rather a laborious and not fully satisfactory solution. For it should be realized that the numerically determined $(\alpha/p)_g$ function, though considered to be equivalent, in certain interval of reduced electric field intensity (K/p) values, to the pencil of specific $(\alpha/p)_s$ curves directly bound to the experiment, is in fact, an approximation of the curves depending upon gas pressure (p). Furthermore, the data needed for this method relate to narrower range of K/P values as compared with the entire range of practically useful values of this ratio for avalanche counters (see refs. [18, 19]). There exists therefore a justifiable need of searching for other more satisfactory solutions.

In order to determine veracious criteria of PPAC spatial charge effect, it turns out that the $\overline{M}_{abs} \times (dE/dx)_d$ product as plotted *vs.* p must faithfully represent the variability of $\overline{M}_{arb} \times (dE/dx)_d$ product for individual d values (see Figs. 5 and 6). To achieve this, those curves determined by the method previously mentioned have been corrected so that the new $\overline{M}_{abs}$ characteristics satisfy now the following requirements:

- the slope of the linear section of every one of them as plotted in the semilogarithmic coordinate system is equal to the slope of the corresponding pulse amplitude characteristic ($\overline{U}_{exp}$);
- the relations between their selected points are exactly the same as for $\overline{M}_{arb}$ curves determined basing upon the experimental $\overline{U}_{exp}$ characteristics;
- the new values are equal to the former ones corrected in relation to the most veracious point chosen before.

Each of the absolute gas gain characteristics plotted in the semilogarithmic system can now be described by the following equation:

(3) $(\log \overline{M}_{abs})_{p=const} = \partial \log \overline{U}_{exp}/\partial U \times U + b_{abs}$

where $\partial \log \overline{U}_{exp}/\partial U$ and b_{abs} coefficients are numerically determined for each characteristic. Precisely these equations, written appropriately for various d values at various p-parameter values, have been used to determine the numerical values of the points in Fig. 6.

In ref. [18], the $\partial \log \overline{U}_{exp}/\partial U$ coefficient has been denoted as $c'_4 = c_4 \log e$. Wherein, using appropriate approximation, the empirical equations for c_4 coefficient have been determined. Now, the b_{abs} coefficient has been treated in a similar manner. Next, by appropriately rearranging equation (3), the general expression has been obtained in form of equations given in Table 2.

The equations of Table 2 describe the linear characteristics in the semilogarithmic coordinate system. This would mean that they only apply to such PPAC operating conditions at which no additional effects occur. Nevertheless, these equations can be used in other cases as well, by appropriately mapping, onto these characteristics, the points from nonlinear sections of experimental curves.