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Investigation of operation of a parallel-plate avalanche chamber with a CsI photocathode under high gain conditions

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We report results of a systematic study of the operational characteristics of a single-step parallel-plate avalanche chamber with CsI photocathode under high-gain conditions at room temperature and 1 atm pressure. Different mixtures of He and Ar with hydrocarbons were tested, as well as with ethylferrocene vapor which are known to form an adsorbed photosensitive layer on the CsI photocathode. The chamber can reach high gains, up to 10^6, has a very good time resolution (500 ps FWHM), and an energy resolution of 8.2% FWHM for 3×10^3 primary photoelectrons with a quantum efficiency of the CsI photocathode of about 20% at 193 nm. Photon feedback, caused by avalanche emission with wavelength longer than 200 nm, was observed for large total charge and found to be nearly independent of the concentration of quencher in the range 7 to 70 Torr. Breakdown appears at a total charge of 10^{10} electrons and is always of the slow type. There is good proportionality up to the breakdown limit.

1. Introduction

It was recently proposed [1] to use CsI photocathodes in parallel-plate avalanche chambers (PPACs). This combination is expected to open new avenues in detector capabilities: very good time resolution and high quantum efficiency in the UV region over large surfaces. This detector has been studied by different groups [2–5] and has shown satisfactory operation under the conditions of moderate gain. Results of these studies suggested the use of PPACs with CsI photocathodes for the readout of BaF_2 calorimeters [6]. Recently parallel-plate avalanche chambers with CsI photocathodes were proposed for BaF_2 pre-shower [#1] detectors [7]; other interesting applications could be as a large surface photon detector for Cherenkov Ring Imaging, astrophysics, and plasma diagnostics. The last applications require operation at very high gain.

We describe in this article the results of a systematic study of the characteristics of a PPAC with a CsI photocathode under high gain conditions (above 10^5).

[#1] Preshower detectors were suggested long ago (see for example Massam, Muller, and Zichichi, CERN 63-25), and are in wide use. It is possible to couple a BaF_2 preshower detector to a BaF_2 calorimeter to make the whole system homogeneous.

2. Installation

The setup used is shown in fig. 1. It contains a test PPAC, a VUV source (or radiation source) and a photomultiplier (PM) to monitor the VUV source. The test chamber contains a BaF_2 crystal ($7\times2.5\times2.5$ cm^3) and a PPAC with a 4 mm gap between electrodes. The anode mesh of the PPAC is 1 mm from the BaF_2 crystal and the cathode is made from a 4 mm thick stainless steel plate, 15 cm in diameter, covered by a 500 nm thick CsI layer. The cathode has two holes of 20 mm diameter, covered by mesh, through which test charges may be introduced into the gap. The test charges are generated by two radioactive sources installed inside the gas container: ^{241}Am and ^{55}Fe. The space between the sources and the cathode plate acts like a conversion region for the primary charges, whose flow can be suppressed by introducing in this region a lead shutter operated from the outside.

A VUV source (pulsed hydrogen lamp) with a duration of 15 ns FWHM creates photoelectrons from the CsI photocathode. In most measurements the VUV light was filtered by a narrow band filter centered at 193 ± 10 nm; this filter simulates the part of the BaF_2 fast scintillation emission to which the CsI is most sensitive. The light also reached a C31000Q photomultiplier through a 3 mm hole made in the photocathode surface, and a CaF_2 window.

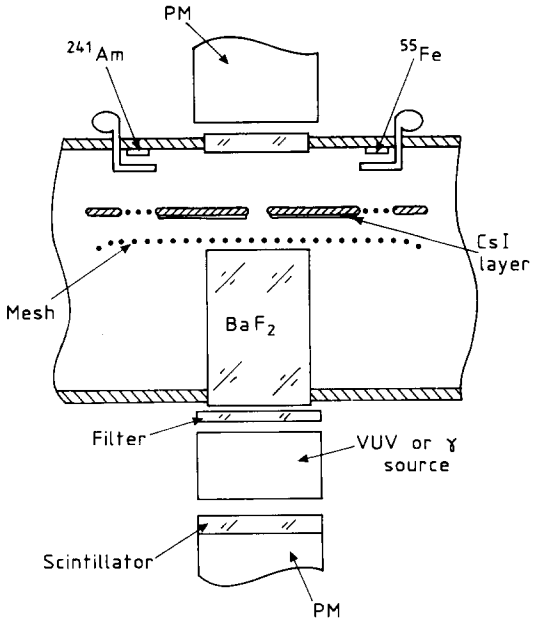

Fig. 1. Schematic view of the experimental setup.

Before installation of the CsI photocathode, the chamber was cleaned by heating under high vacuum for 24 hours (50 °C and 10^{-5} Torr) and the gas system was thoroughly flushed. This was done to remove water and air from the system which can damage the CsI photocathode.

A small on-line data acquisition system was used to measure the total signal charge, the initial avalanche charge, the lamp pulse charge, the chamber response time, and the feedback level. The total charge was measured through an ORTEC model 142 charge-sensitive preamplifier; the initial avalanche charge was measured by choosing the gate width of the CAMAC charge-sensitive ADC such that the avalanche successors lie outside the gate pulse; the lamp pulse charge was measured by feeding a signal proportional to the lamp discharge current to the ADC. The feedback level was estimated by integrating the chamber signal with a 100 ns time constant; the successors appeared as a series of "steps" in the integrated signal. The ratio of the first step height to the total height was directly observed on the oscilloscope, providing an estimation of the feedback level ηG (see below). The chamber response time was measured by the time difference between the leading edge of the lamp monitor signal (detected by fixed-threshold discrimination) and the peak of the initial avalanche signal from the chamber. The peak detector was implemented by differentiating the chamber signal with a 5 ns time constant and detecting the zero-crossing with a fixed-threshold discriminator.

3. Measurements

3.1. Quantum efficiency

The quantum efficiency (QE) of the CsI photocathode was estimated in two independent ways:

– The response of the monitoring PM was compared with the response of the chamber, corrected for solid angle differences and the PM's QE. The primary charge in the PPAC, produced by the VUV lamp, was about 3×10^3 electrons. On the PM, having 2% of the acceptance of the chamber, we measured 50 photoelectrons. Assuming equal quantum efficiencies for the chamber and PM, one would expect 2.5×10^3 photoelectrons created by the chamber, which is close to the measured value of 3×10^3. In this way we conclude that the QE of the chamber is comparable to the QE of the PM, i.e., at least 20% at 193 nm. The fluctuations in the lamp's bright spot position may introduce an error of a factor of ~ 2 in the solid angle estimation. Another possible source of error comes from the lack of calibration of the PM's photocathode.

– Cosmic ray muons incident on the BaF_2 crystal produce a known amount of energy loss (~ 7 MeV/cm). Comparing the number of photoelectrons released from the CsI photocathode by the BaF_2 scintillation (peaked at 193 nm) with the signal from an additional PM installed in contact with the crystal, we estimated that 1 MeV energy loss created about two photoelectrons in the PPAC. Using the calibration from ref. [5] we calculated a QE between 15 and 20% which is in reasonable agreement with the previous result.

Ethylferrocene (EF) vapor is known to form an adsorbed photosensitive layer on the CsI photocathode, and increase its QE. We used a specially cleaned EF [#2], which we further cleaned by flushing with clean, dry gas for 24 hours. The cleanliness of the EF is important because it has a low vapor pressure (10^{-2} Torr at 20 °C). After the introduction of EF, we observed a 15% increase in the PPAC signal, with unity gain. However, the PM signal decreased by 30% due to light being absorbed by EF layers on previously transparent surfaces. (Since EF has a vapor pressure of only 10^{-2} Torr, the absorption in the gas is negligible). Taking this light loss into account, we estimate that the EF increased the photocathode's QE by $\sim 40\%$.

3.2. Feedback investigation

The evolution of the PPAC signal as a function of the applied voltage is shown in figs. 2a–2d. From the timing characteristics of the signal we are convinced

[#2] Obtained from the Metallorganic group of the Moscow State University.

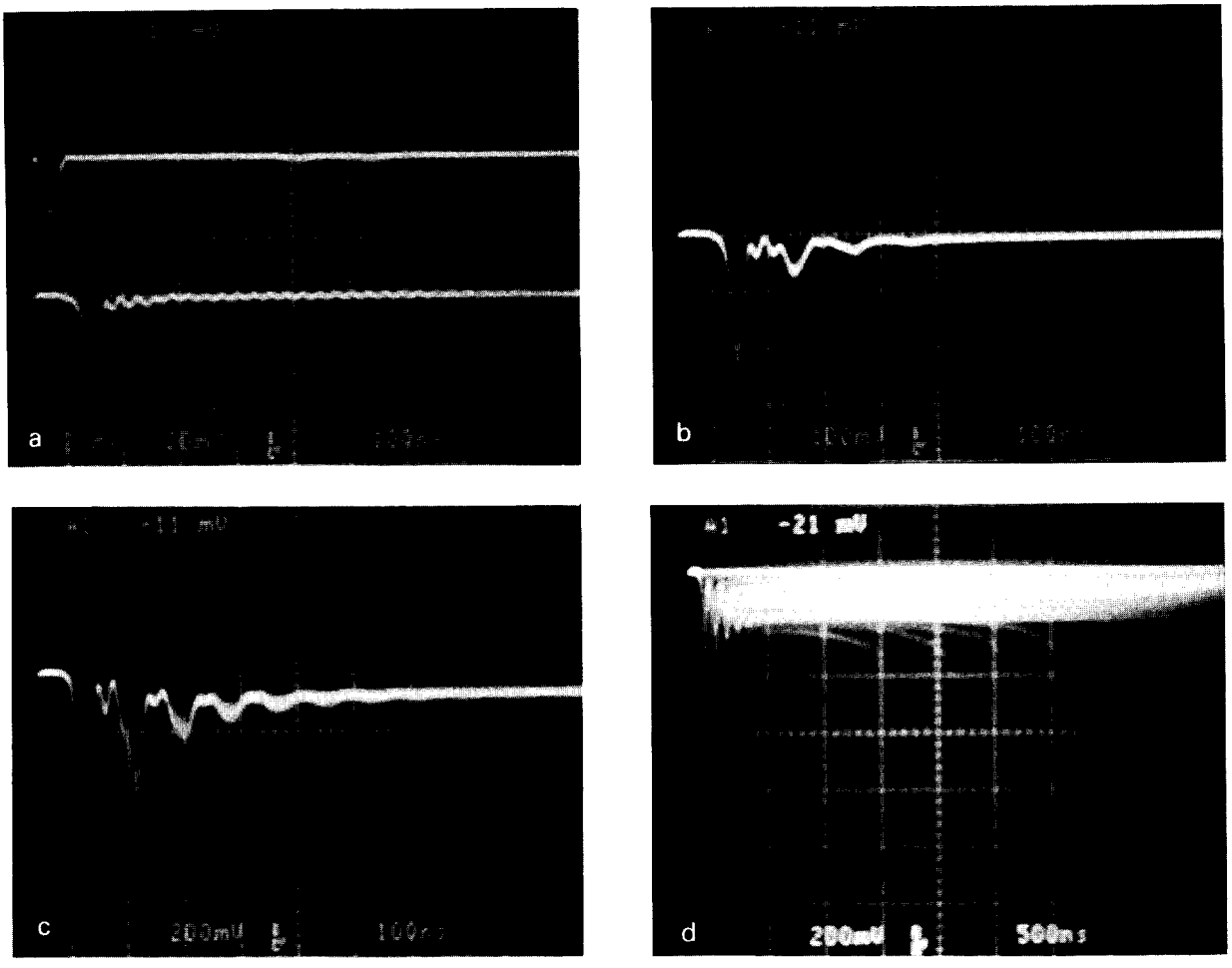

Fig. 2. Typical chamber signals, as detected with a fast current preamplifier: (a) chamber signal delayed after the PM signal (top) by the avalanche time, (b) ~ 25% feedback – our standard level for feedback measurements, (c) many feedback successors, (d) slow breakdown.

that the observed successor avalanches originate from photon feedback. The relations between the primary charge, the initial avalanche and the first successor are:

$$N_1/N_0 = G \quad \text{and} \quad N_2/N_1 = \eta G,$$

where G is the gas gain, N_0 is the primary charge ($\sim 3 \times 10^3$ electrons), N_1 is the charge in the primary avalanche, N_2 is the charge in the first successor, and η is the feedback efficiency, i.e., the number of feedback photoelectrons per electron in the initial avalanche; η is dependent on the gas gain. For quantitative estimation of the feedback efficiency, η, as a function of the gas constituents, we measured the total charge in the avalanche for a fixed feedback level (ηG) of 25%. Since the primary charge is known, the gas gain can be calculated, allowing an estimation of η.

The raw data showing the charge at 25% feedback and at breakdown for different mixtures are shown in figs. 3 and 4. These data were taken with gas gains ranging from 2×10^5 to 4×10^6. The feedback is essentially independent of the concentration of hydrocarbons in the range 6–60 Torr. It depends slightly on the noble gas used, being higher for argon than for helium. We could not obtain reproducible data for mixtures containing Ar and CH_4, which is known to be a bad quencher; with the addition of EF this problem disappeared. The data for gases containing EF do not differ strongly from the data obtained without EF, except in the case of a mixture of Ar and CH_4.

No trace of ion feedback was observed up to the breakdown limit.

3.3. Light emission

The VUV light emission from the avalanches (in the range 120–170 nm) for these mixtures was previously

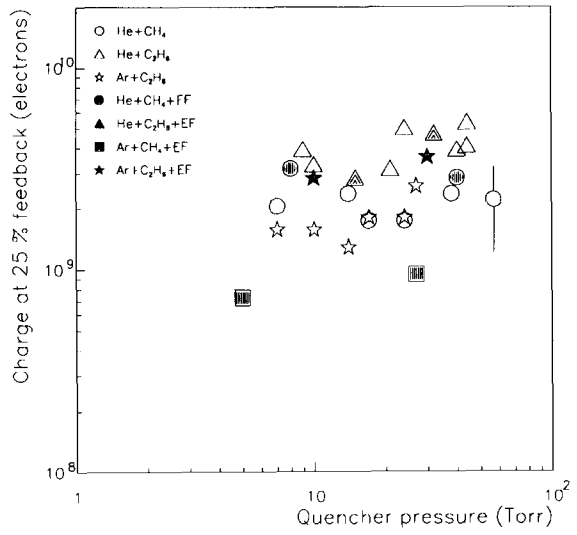

Fig. 3. The charge at which 25% feedback occurs the quencher pressure, shown for various gas mixtures. For readability, error bars are shown for only one point. The other errors are similar.

measured [8], as well as the feedback efficiency in a PPAC without a photocathode [9]. Under these conditions the feedback efficiency decreases rapidly, by several orders of magnitude with increasing concentration of hydrocarbons in the gas (range 6–60 Torr), and a similar behavior is observed for the VUV light emission. In the present case such behavior is not observed. Since the QE, for UV light, of the CsI photocathode is several orders of magnitude higher than for the stainless steel meshes used in the previous measurements, we assume that in our case emission at longer wavelengths (longer than 175 nm) is responsible for the feedback.

In order to verify this, we made measurements of the light emission in the range 200–500 nm, using the same PM that was used for monitoring the lamp emission. This is possible because the chamber emission is delayed from the lamp signal by the avalanche gap-crossing time, around 100 ns. The results (ratio of light to charge) are presented in fig. 5. Since the measurements were done at different gas gain and the ratio of light to charge strongly depends on gain [10], the dispersion of the points is large, but the same qualitative features as observed for the feedback efficiency can be recognized: weak dependency on quencher concentration and higher yield for mixtures containing argon than for those containing helium.

This behavior, which contrasts with the behavior observed for VUV emission, is similar to what was observed for the molecular emission in gases containing TEA, TMAE, or H_2O vapors [10]. This allows us to suggest that in our case the avalanche emission, in the region $\lambda > 200$ nm, is not fragment emission but molecular emission. The fact that molecular emission is much stronger than fragment emission is natural, since generally the excitation thresholds are lower and the cross sections are higher for molecular emission. These results suggest an explanation of why previous attempts [11] to use gaseous photodiodes failed to get high gain. In that case the photocathode had very high efficiency in the visible region and probably was highly affected by molecular emission.

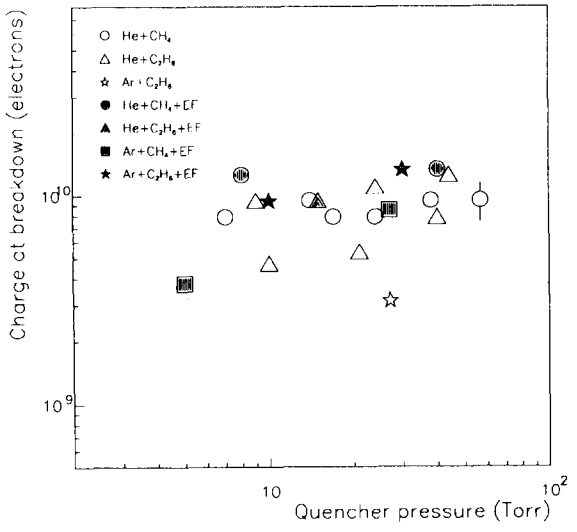

Fig. 4. The charge at which breakdown occurs the quencher pressure, shown for various gas mixtures. Error bars are shown for only one point.

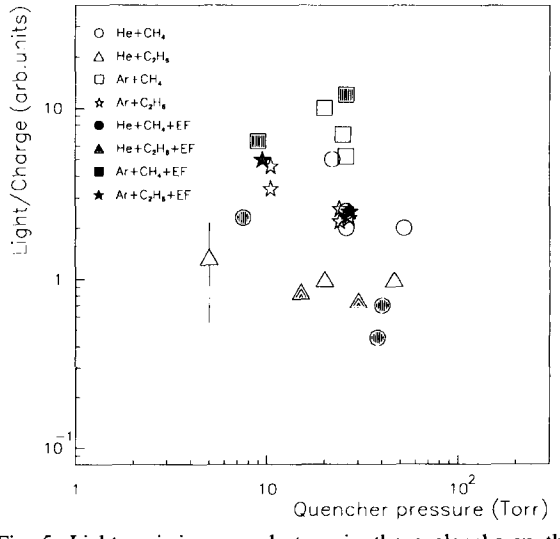

Fig. 5. Light emission per electron in the avalanche vs the quencher pressure. Error bars are shown for only one point.

3.4. Breakdown

In the case of a PPAC with a CsI photocathode only slow breakdown is observed (as illustrated in fig. 2d), even at high concentration of quencher. We should note that without photocathodes fast breakdown dominates above ~ 10 Torr [9]. Slow breakdown appears when $\eta G = 1$, so the gain at which breakdown takes place is related to the feedback efficiency. A convenient criterion of breakdown could be the total charge in the avalanche (primary avalanche plus successors). This measurement is presented in fig. 4.

Breakdown appears at very high total charge, up to 10^{10} electrons spread over the ~ 4 cm^2 surface of the photocathode. This limit slightly depends on the concentration of quencher and on the gas constituents. Since the primary charge is estimated to be 3×10^3 electrons the maximum gain reaches the order of magnitude of 10^6, which is remarkable in a single-step configuration and in view of the high photosensitivity of the chamber. Considering that both the initial charge and the feedback charge are not concentrated, but are spread over the surface of the photocathode, this observation fits well into the simple theory of breakdown in PPACs presented in ref. [9].

Since slow breakdown develops in a few μs, it may be possible for practical applications to use an active protection against breakdown, by pulsing off the voltage in the amplifying gap when the current grows well above the normal avalanche level.

3.5. Energy resolution

An important characteristic of this detector is its energy resolution, which we measured for most of the mixtures used. Owing to the large fluctuations of the UV lamp emission we had to monitor the lamp signal (current or light emission) in order to correct the data; current proved to be more accurate than light for this purpose. A signal proportional to the lamp discharge current was fed to a CAMAC ADC, along with the fast component of the PPAC signal (initial avalanche) and the signals were divided after acquisition.

Typical results are presented in fig. 6: the insets in the left side of the figure present the raw spectra of the chamber and lamp, while the main graph shows the normalized PPAC energy resolution. The typical energy resolution is between 8 and 10% FWHM, depending on the gas mixture and the chamber gain. These values are not unexpected, since the statistical error involved in our 3×10^3 primary charge is around 5% FWHM. We attribute the excess dispersion to the well know effect that gain fluctuations can spoil the expected energy resolution by a factor of 2, especially at high gain. Measurements done at gain 1 with a much more energetic source confirm this [12]. Also, the large lamp

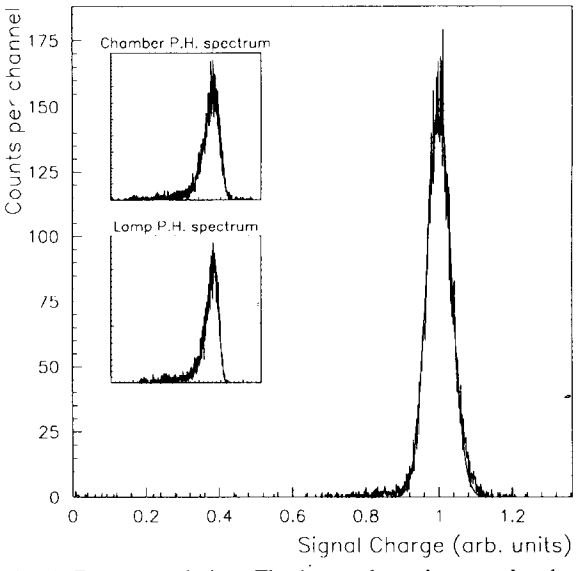

Fig. 6. Energy resolution. The insets show the raw chamber and lamp distributions, and the main plot shows the normalized chamber distribution (corrected for lamp fluctuations).

fluctuations certainly cannot be removed completely. As a check on the energy resolution measurements, we verified that when the primary charge was artificially reduced by a factor of 4, the energy resolution decreased by a factor of ~ 2, as expected.

3.6. Time resolution

We also made time resolution measurements, using the electronic setup described above. A typical spectrum is presented in fig. 7; the time resolution is ~ 500 ps FWHM or better for all mixtures measured. This is at least ten times better than reported results at low pressure [3], and can be simply related to the large amount of primary and total charge achieved in our setup. When we reduced the primary charge by a factor of 4, the timing resolution was worsened by a factor of ~ 2.

3.7. Fragility

It is know that the CsI photocathode can be damaged by exposure to air. We found, however, that an adsorbed layer of EF will protect it: after an exposure to air for 2 hours, the QE of the CsI + EF photocathode was decreased by only 20%. However, after flushing pure gas for 24 hours, the QE returned to its previous value. The CsI photocathode can also be damaged by high voltage sparks between the anode mesh and the photocathode; we found that 10 minutes of sparking (several thousand sparks) reduced the quantum efficiency by a factor of two. The long term aging properties of CsI + EF have been previously investigated [13],

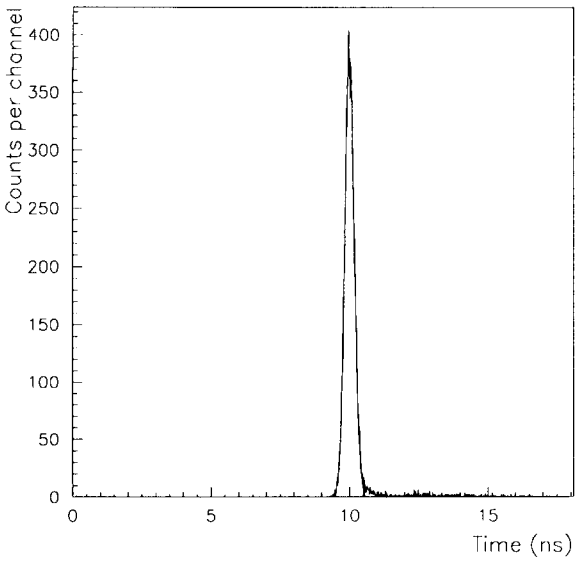

Fig. 7. Time resolution; the FWHM is 500 ps.

and it was found that after extended corona discharge corresponding to ~ 100 mC/cm^2 of accumulated charge, the QE decreased by a factor of ~ 2. It should be noted, however, that that investigation was done with a single wire tube chamber, not a PPAC, and should be repeated for the PPAC geometry where the electric field near the cathode is considerably higher.

4. Conclusion

We have demonstrated that a single-step PPAC with a CsI photocathode can work at high gain and has good energy and time resolution. These results demonstrate that the PPAC structure can be used in crystal calorimeter and pre-shower detectors. Another feature is that one can work with a light gas mixture, as for example He + 7 Torr CH_4; this is very convenient for the rejection of direct ionization released by charged particles.

Excellent timing resolution was achieved in proportional mode and can be widely used in practice.

Acknowledgements

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