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Successful implementation of fast preamplifiers in a positron lifetime spectrometer

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Abstract

A method to improve the long-term stability of fast coincidence apparatuses, like a positron lifetime spectrometer, is reported. Ageing of the photomultiplier tubes (PMT), i.e., nonreversible degradation of the gain, can be slowed down by lowering the supply voltages over the PMTs and by compensating the lower gain with fast preamplifiers set at the anodes. The timing characteristics of the PMTs can be preserved by using voltage dividers with which the voltage in the input optics of the PMTs remains high enough for good photoelectron collection efficiency (for XP2020 above 300 V). With this setup, the anode current and the rate of gain degradation can be reduced at least by a factor of 20 with no loss in the time resolution of the spectrometer.

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Keywords: Fast coincidence apparatus; Positron lifetime spectrometer; Fast photomultiplier tube; Fast preamplifier

1. Introduction

Over the last few decades, positron annihilation spectroscopy has yielded a lot of invaluable information about the properties of point defects in solids [1]. The electronic structure of the annihilation site leaves a fingerprint in the annihilation radiation. Combined with theoretical electronic-structure calculations, detailed information on especially vacancy-type defects has been obtained.

Positron lifetime is the variable which has proven to be most informative. An increase in the lifetime is an unambiguous signal of open-volume defects in the specimen. The unambiguity of the interpretation is the asset of the technique compared to many others applied in defect studies of solids.

Typically, the positron lifetime is of the order of 10^{-10} s. It is usually measured as a time difference between two γ-quanta: one is emitted simultaneously with the positron from the radioactive source (commonly ^{22}Na) and the other is one of the annihilation γ-quanta. The apparatus is a conventional fast coincidence spectrometer with a time resolution of about 200 ps (full-width at half-maximum, FWHM). The photons are detected with fast scintillation detectors which normally are composed of fast plastic or BaF_2 scintillators and linear-focussed photomultiplier tubes (PMT).

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Positron lifetime spectra usually consist of many superimposed exponential distributions. Especially in semiconductors, the decay times are often rather close to each other. To facilitate the resolution of the components and their intensities, good statistical accuracy is of utmost importance [2–4]. High counting rate is therefore desirable. However, increasing the counting rate too much brings about a problem: the average anode current in the photomultiplier tubes increases, leading to nonreversible degradation of the PMT gain. This results in long-term creep of the apparatus deteriorating the quality of data.

According to manufacturers the deterioration of the PMT gain is due to too strong electron bombardment of the last few dynodes. This causes the wear out of the surface layers which decreases the secondary electron emissivity. According to Photonis (formerly Philips Photonics), an average current of 30 μA leads to a decrease of gain by a factor of two in about 5000 h [5]. The gain reduction of the tube seems to be a function of the total charge taken from the anode [5]. Thus with a smaller anode current the lifetime of the tube is longer. To achieve high stability, manufacturers recommend the average anode current to be maintained below 1 μA [5–8]. With a modern positron lifetime apparatus this corresponds to a counting rate of the order of 50 cps which leads to very long measurement times. Usually, the counting rate is hundreds of counts per second, which is known to cause deterioration of the gain and the stability of the apparatus [9].

A way to slow down the degradation of the gain is to decrease the anode current by lowering the supply voltage over the PMT and by compensating the loss in gain by implementing a fast preamplifier at the anode. Fast preamplifiers have been used for years to boost photomultiplier signals in various applications. Recently, Bečvář et al. reported utilizing fast low-gain amplifiers in a positron lifetime spectrometer to compensate for decreased pulse heights [9]. However, they did not lower the operating voltages over the PMTs. In fast timing, like positron lifetime spectroscopy, the natural question that arises is whether this is feasible without impairing the time resolution of the apparatus. Typically, PMTs are driven with as high a voltage as convenient, rather than a lower one. This is done because it is well known that the timing properties of the PMT generally improve with increasing voltage [5,7,10]. In positron lifetime spectrometers, however, the time spread related to the production and collection of light (in the reasonably sized scintillators) is believed to be the dominating factor on the resolution. Therefore, the resolution may not necessarily worsen very rapidly with decreasing PMT voltage. On the other hand, the linearity of the PMT pulses, essential for the timing electronics, improves with decreasing supply voltage. This is due to the fact that the peak current in the pulse decreases more strongly with voltage (as V^9) than the current linearity limit (as $V^{2\cdots3}$) [5,6]. When the PMT is operated in the conventional way, 1-V anode pulses originating from 1-MeV γ-radiation are not necessarily in the linear region [11]. Undoubtedly, when decreasing the supply voltage, the time spread originating in the PMT eventually starts to dominate leading to a nonacceptable degradation of the resolution. Also, the amplifier noise may become a limiting factor at too low signal levels.

In this work, we have studied the effect of the PMT operating conditions on the resolving power of the apparatus. The main object was to investigate if the average anode current can be lowered without sacrificing the resolution. As photomultipliers we used variants of the classic fast linear-focused PMT XP2020 manufactured by Photonis. We found that the supply voltage, and thereby the gain and the average anode current can be lowered significantly, at least by a factor of 20, without deterioration of the time resolution. Two conditions, however, have to be fulfilled: the voltage at the input optics of the PMT has to be high enough (for XP2020 this means above 300 V), and the anode pulse amplitude must be substantially higher than the noise level at the input of the preamplifier, which means pulses of some tens of millivolts. Implementation of e.g. preamplifiers with gain 20 enables the decrease of the average anode currents typically below 1 μA which improves notably the long-term stability of a positron lifetime spectrometer.

2. Experimental

Our experiments were performed with fast coincidence apparatuses. The idea was to vary the conditions of one of the detectors, keeping the other one fixed, and investigate the changes in time resolution. During the course of the experiments, three different reference detectors were used. Therefore, the time resolution values reported in Sections 3.1–3.3 cannot be compared between different series (sections).

In all experiments, plastic cylindrical scintillators coated with white diffusely reflecting TiO_2 paint were used in both detectors. In the reference detector, the scintillator material was ZL-236 (Zinsser Analytic Ltd) and in the one under investigation NE-111 (currently BC-422 from Bicron). The scintillator sizes used in different experiments are given in Section 3. The scintillators were coupled on fast linear-focused PMTs XP2020 or XP4222B manufactured by Photonis. The type XP4222B is a selected XP2020 with a slightly higher quantum efficiency and a user-adjustable grid-g2 potential. As to the conclusions of the experiments presented here, the differences in the two PMT types are negligible. The timing signal was always taken from the anode.

The measurement electronics of the spectrometer was the same in each measurement series. The anode signals were fed into differential constant-fraction discriminators (CFD, Ortec model 583), the time-to-amplitude conversion was done with Ortec 566, and the multichannel analyzer was Ortec 916 Ace.

Due to the low average atomic number of plastic scintillators, Compton-scattering is the predominant interaction mechanism. Hence, no photopeaks are observed, and the energy windows are set at the upper parts of the Compton-continua resulting from the interactions. When using the conventional ^{22}Na source in the positron lifetime experiment, the start detector is set to observe the 1275-keV γ-quanta emitted by the source nucleus, and the stop detector the annihilation photons of energy 511 keV.

^{60}Co is a nucleus which emits two γ-quanta of energies 1173 and 1333 keV practically simultaneously. The response of a positron lifetime spectrometer to this source is a good measure of the resolving power of the apparatus. In the test measurements presented in Sections 3.1–3.3, ^{60}Co was used as a γ-source. To improve the sensitivity of the apparatus to the modifications, the energy windows were set in both detectors at the 1275-keV Compton-edge, and not as in a positron lifetime measurement. The width of the windows was 50%. In this paper, the full-width at half-maximum (FWHM) of the spectrum is used to quantify the time resolution.

Each time the operating conditions of the spectrometer were changed, the time resolution was optimized in the following way. Firstly, the voltages of the focusing grid g1 and the second dynode d2 were adjusted to give maximum anode pulse height. This setting is known to be very close to optimum with respect to timing characteristics [12]. Further, the walk setting and the CF-delay of the CFD leading to best resolution were searched for. To ensure statistical reliability, at least 10^5 counts were always collected to the resolution function spectrum.

Three fast preamplifiers were used in this work. Ortec VT120A (gain 200) and VT120C (gain 20) are noninverting ones meant for boosting fast linear signals, e.g. from photomultipliers [13]. The rise time in both models is below 1 ns, which is short enough such that the anode signal is not modified by the amplifier. The noise at the input is lower than 20 μV rms for these amplifiers. The third preamplifier was LeCroy VV100B with gain 10 [14]. Its rise time is below 2 ns and its wideband noise is lower than 50 μV rms.

3. Implementation of fast preamplifiers

3.1. Effect of a preamplifier

A preamplifier connected at the anode of a fast photomultiplier tube adds a small amount of noise in the pulse. To study the effect of the preamplifier alone, two measurements were performed. Firstly, the time resolution of the spectrometer was measured normally with the anode signal of the test detector connected directly to the discriminator. Secondly, a passive attenuator circuit with an attenuation of 20 and an Ortec VT120C preamplifier with gain 20 were connected in cascade between the anode and the discriminator. In the latter case, the amplitude of the attenuated anode signal corresponding to the lower limit of the energy window was 30 mV. The resulting ^{60}Co-spectra are shown in Fig. 1. As seen, they are identical down to the FW100M. The FWHM is 225 ps. The small tail in the spectrum with the cascade is evidently due to ringing caused by the self-made attenuation circuit (without the attenuator, this kind of anomaly has not been observed with similar-sized pulses). The data indicate that when the input signal to the preamplifier is of the order of 50 mV or larger, the amplifier does not induce any significant time spread in the apparatus.

3.2. Importance of the cathode to first-dynode voltage in the PMT input optics

The timing capability of a PMT is characterized by the electron transit time spread (TTS). It describes the transit time fluctuation of pulses initiated by single photoelectrons. In a fast PMT, the TTS is usually of the order of a few hundred picoseconds. The time spread originates from varying initial velocities and directions of electrons when they are emitted from the photocathode and dynodes, and also from different path lengths along individual trajectories [5]. The main fraction of the TTS stems from the input electron optics of the PMT (the region between the photocathode (pc) and the first dynode (d1)). The time spread caused by the electron multiplier is smaller because of the increased number of electrons in the pulse leading to a better statistical accuracy.

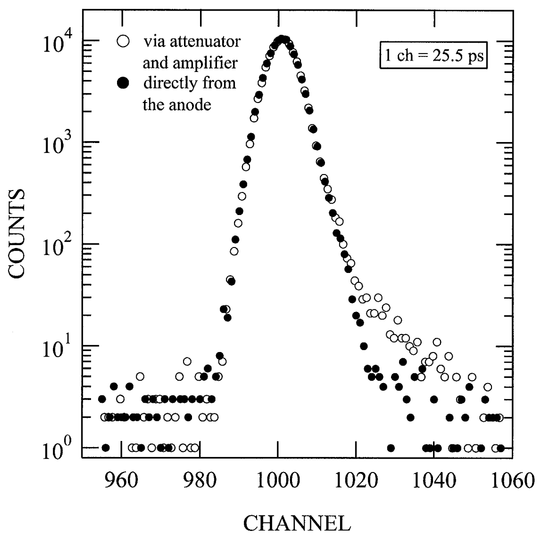

Fig. 1. Effect of a fast preamplifier Ortec VT120C on the time resolution function measured using ^{60}Co as a γ-source. The tail in the data acquired using the attenuator–amplifier combination is presumably an anomaly originating from the attenuator.

The TTS can be decreased by increasing the electric fields between successive stages. This is based on two reasons. Firstly, from simple kinematic arguments, the transit time difference between electrons with different initial velocities or different path lengths decreases with increasing electric field strength. Secondly, the gain of the dynodes increases with voltage (as $V^{0.75}$) leading to a more rapid increase in the number of electrons in the pulse. This again results in a decrease in the time spread coming from the later stages.

At a given total gain of the PMT the best timing performance is obtained with a tapered voltage distribution, in which the voltages at the first two stages are highest [10,15]. This is utilized in the ultra-rapid version XP2020/UR, for which Photonis suggests as the voltage U_{pc-dl} at least 600 V instead of 300 V with normal XP2020 [6,16]. There are no data on the influence of decreasing U_{pc-dl} below the recommended values, which is the relevant question from our point of view.

In the experiment discussed in this section, our aim is to study the effect of the voltage U_{pc-dl} on timing. To avoid changes in time resolution related to the timing electronics and PMT linearity, we set the total supply voltage in all measurements such that the anode pulse amplitude at the upper limit of the energy window was about 1.5 V. The different voltage distributions were accomplished by modifying the resistance between the photocathode and the first dynode in the divider chain. The scintillator size in the detector under test was $\phi 30 \times 20\,\mathrm{mm}^3$.

The results showing the time resolution of the spectrometer (FWHM) as a function of the U_{pc-dl} are presented in Fig. 2. The time resolution obtained with the voltage divider C that Photonis

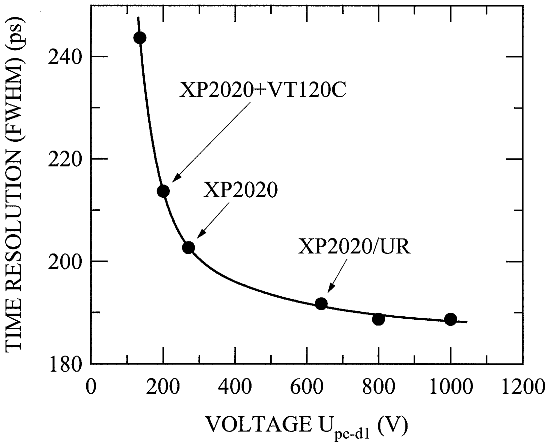

Fig. 2. The time resolution as a function of the voltage between the photocathode and the first dynode in the test detector photomultiplier. The points marked with "XP2020" and "XP2020/UR" were obtained using voltage dividers C recommended by Photonis for XP2020 and XP2020/UR, respectively. The line is to guide the eye.

recommends for fast timing applications with XP2020 is 203 ps (marked with "XP2020"). With this is divider the voltage $U_{pc\text{–}dl}$ is 270 V, just below 300 V that the manufacturer quotes as the minimum voltage for good electron collection efficiency in the input optics. The divider designed for the UR tube increases the $U_{pc\text{–}dl}$ up to 640 V and improves the resolution to 192 ps (point marked with "XP2020/UR"), This improvement is in agreement with the results reported by Moszynski [17]. However, further increase in the voltage in the input optics does not significantly enhance the resolving power of the spectrometer. This can be easily understood, since with decreasing time spread of the PMT its contribution to the total time resolution becomes negligible compared with that of the scintillators.

If a VT120C preamplifier (gain 20) is connected to the tube driven with the C divider for XP2020, the voltage $U_{pc\text{–}dl}$ decreases down to 200 V and the resolution worsens by about 14 ps. Here, as a result of lowering the total supply voltage over the tube (by about 350 V), the time spread in the electron multiplier part of the tube also increases. The main contribution is, however, obviously due to the decrease in $U_{pc\text{–}dl}$. Further lowering $U_{pc\text{–}dl}$ to 135 V leads to a considerable deterioration of the time resolution to 243 ps. At this low a voltage, the worsening probably results, apart from the increase in the TTS, especially from the substantial decrease in the photoelectron collection efficiency [18]. That is, many of the photoelectrons do not reach the first dynode at all.

Fig. 2 demonstrates that the time resolution worsens with decreasing voltage in the input optics. The suggestion by Photonis to apply at least 300 V between the photocathode and the first dynode is clearly supported by the data. An increase of $U_{pc\text{–}dl}$ from 300 V towards 800 V improves the total resolution still noticeably but beyond that no improvement is seen.

3.3. Performance with a fast preamplifier at low operating voltages

As shown above, if the supply voltage over an XP2020 driven with the normal C divider is decreased and the loss in gain compensated with a preamplifier (gain 20), the resolution worsens by about 14 ps. This degradation is due to the change in the operating conditions of the PMT, not due to the preamplifier. Based on the data in Fig. 2, a prerequisite of a successful implementation of a preamplifier in the spectrometer without impairment of the time resolution, is that the voltage $U_{pc\text{–}dl}$ remains above 300 V. Following this reasoning, we designed a base with which the voltage $U_{pc\text{–}dl}$ is higher than 300 V whenever the supply voltage is above 1000 V. The circuit diagram is shown in Fig. 3. In this base, the voltage $U_{pc\text{–}dl}$ is 33% of the supply voltage over the PMT whereas with the recommended C base it is only 19%.[1]

To improve the sensitivity of our test to changes in the supply voltage over the PMT, we used a spectrometer with a somewhat better time resolution, about 160 ps. Scintillators of size $\phi 25 \times 15\,mm^3$ were mounted in both detectors. In Fig. 4 we present the time resolution (FWHM) of the test spectrometer as a function of the high

[1] Photonis intends to develop 8- and 10-stage versions of the XP2020 tube [19]. These would be most suitable for a spectrometer with fast preamplifiers since then the interdynode voltages would inherently be higher.

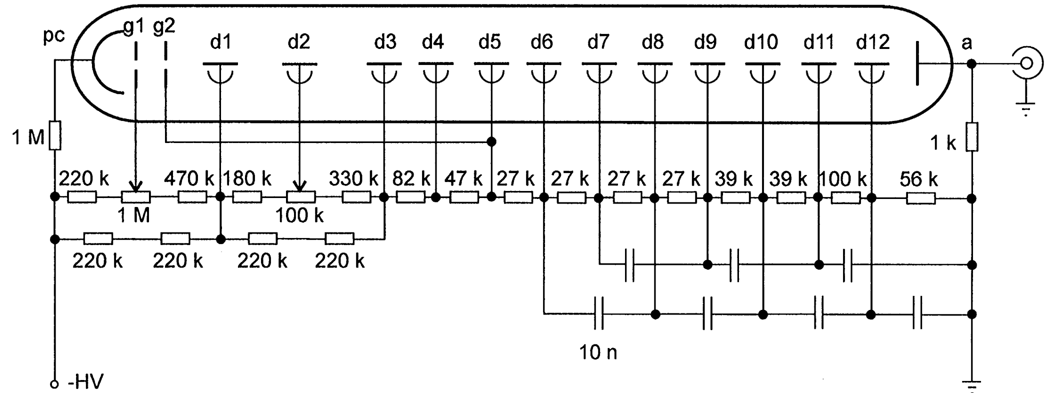

Fig. 3. The PMT base for Photonis XP2020 with which the voltage between the photocathode and the first dynode is above 300 V with supply voltages over 1000 V. All the capacitors are 10 nF. The results shown in Fig. 4 were measured using this base.

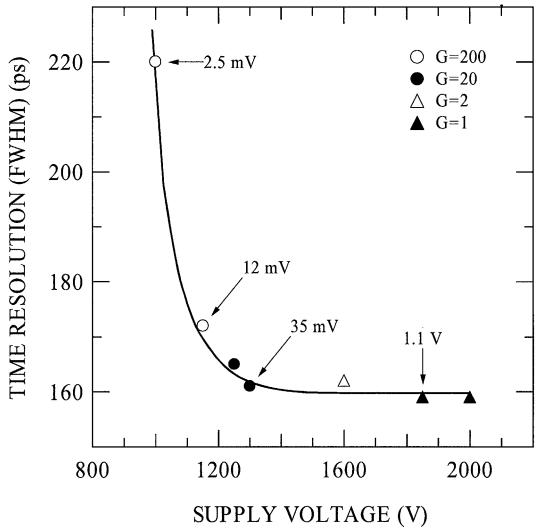

Fig. 4. The time resolution as a function of the operating voltage over the test detector photomultiplier. The nonamplified anode pulse amplitudes at the lower limit of the 50% energy window are given. The markers denote the preamplifer gain in each measurement. The line is to guide the eye.

voltage over the test tube. The different markers in the figure indicate the amplification used at each point. A gain of 2 was realized by connecting a $10\times$ attenuator and a VT120C in cascade. The anode pulse amplitudes at the lower limit of the 50% energy window have been marked in the figure. It can be seen that the time resolution is practically independent of the operating voltage over a very wide range, between 1250 and 2000 V. In agreement with the results of Fig. 2, the time resolution with the modified base does not worsen when using the VT120C: with the amplifier the resolution is 161 ps (at 1300 V) whereas without one it is 159 ps (at 1850 or 2000 V).

Below 1200 V the resolution worsens rapidly from the 160 ps level to a value of 220 ps at 1000 V. Besides the increase of the FWHM, also the shape of the resolution function becomes distorted below 1200 V. One reason for the deterioration of the resolution may be that the preamplifier input noise becomes important as the anode signal shrinks to the millivolt level. At 1000 V the anode pulse amplitude at the lower edge of the energy window is 2500 μV which is only about 100 times larger than the rms noise amplitude at the amplifier input.

The data in Fig. 4 clearly show that the supply voltage of the PMTs is not an important parameter in a spectrometer with scintillators in the cm-size range. This holds under two conditions. Firstly, the voltage in the input optics of the PMT must be high enough to enable good photoelectron collection to the first dynode. Secondly, the pulse amplitudes must, of course, be sufficiently large compared with the noise level of the amplifiers. When using the Ortec VT120C amplifier, the adequate anode pulse amplitude is some tens of millivolts.

3.4. Fast preamplifiers in a positron lifetime apparatus

As a final test of the feasibility of a spectrometer with fast preamplifiers, we implemented two VT120C amplifiers in a spectrometer with large scintillators. As expected on the basis of the results discussed above, the time resolution does not degrade. In Fig. 5, a lifetime spectrum measured in bulk InP is shown. 2×10^6 counts were collected to the spectrum using a 30-μCi ^{22}Na positron source enclosed between 5-μm Al foils. After subtraction of annihilations in the source and the background, the analysis reveals a lifetime of 245 ps, consistent with previous results [20]. The fitted FWHM of a Gaussian resolution function is 195 ps. The quality of the data is similar to that measured with the same spectrometer without preamplifiers.

A LeCroy VV100B fast preamplifier with a gain of 10 was also tested in the spectrometer. No difference compared to VT120C was observed.

We have now used the VT120C amplifiers in the spectrometer for three years. Before the implementation, the average anode currents in the PMTs were 10 μA in stop and 23 μA in start, at a coincidence count rate of 500 1/s. 10 μA current corresponds to a total singles rate of about 5×10^4 1/s when the pulse amplitude at the Compton edge of the 1.275-MeV γ-quanta is 2 V. Operation with such high currents was found to lead to an unsustainable instability of gain: in half a year, the gain in both PMTs decreased by 25–30%. With amplifiers, the gain still decreases, but at a considerably slower rate.

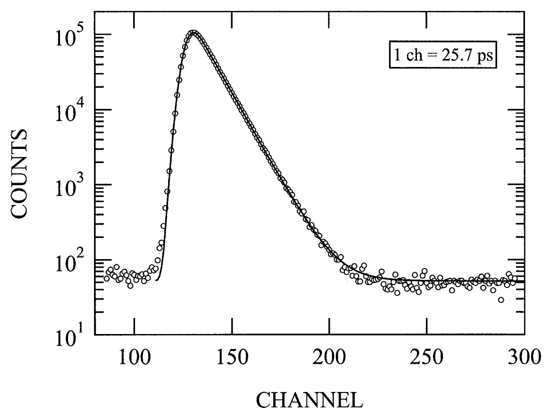

Fig. 5. Positron lifetime spectrum in InP measured with a spectrometer in which two fast Ortec VT120C preamplifiers were used at the anodes. The solid line illustrates the best fit of a single exponential lifetime component together with the source components and the background convoluted with a Gaussian resolution function.

4. Conclusions

In a fast coincidence system, problems arise due to ageing of photomultipliers, especially at high count rates. This problem can be alleviated by using a smaller operating voltage and fast amplifiers to compensate for the loss in gain. This study shows that in this way the current in the photomultipliers can be reduced by a factor of 20, without affecting the time resolution, provided the voltages at the input optics of the photomultipliers are kept high and the anode pulse amplitudes are at least some tens of millivolts. Typically, this corresponds to lowering the average anode current to the μA level at which the rate of degradation of PMT gain is known to be very low.

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