Lead fluoride Cherenkov detector read out by avalanche photodiodes for measuring the intensities of pulsed antiproton beams

Y. Murakami\textsuperscript{a,1}, H. Aghai-Khozani\textsuperscript{b,2}, M. Hori\textsuperscript{b,*}

\textsuperscript{a}Department of Physics, School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, 113-0033 Tokyo, Japan
\textsuperscript{b}Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany

Abstract

A Cherenkov detector based on an array of five lead fluoride (\(\beta\)-PbF\(_2\)) crystals of size 30 mm \(\times\) 30 mm \(\times\) 160 mm read out by reverse-type avalanche photodiodes (APD’s) of active area 10 mm \(\times\) 10 mm was used to measure the flux of secondary particles emerging from the annihilation of pulsed beams of antiprotons at the Antiproton Decelerator of CERN. We compared the relative photon yields of radiators made of \(\beta\)-PbF\(_2\), fused silica, UV-transparent acrylic, lead glass, and a lead-free, high-refractive-index glass. Some p-i-n photodiodes were also used for the readout, but the output signals were dominated by the nuclear counter effect (NCE) of secondary particles traversing the 300 \(\mu\)m thick depletion regions of the photodiodes. Smaller NCE were observed with the APD’s, as the maximum electronic gain in them occurred predominately for electron-ion pairs that were generated in the thin p-type semiconductor layer that proceeded the p-n junction of high electric field where amplification took place.

Keywords: Lead fluoride, Cherenkov detector, antiproton, avalanche photodiode

1. Introduction

The Atomic Spectroscopy and Collisions Using Slow Antiprotons (ASACUSA) collaboration has recently measured the cross sections \(\sigma_{\text{tot}}^A\) of antiprotons with an incident kinetic energy \(E \sim 5.3\) MeV annihilating via in-flight nuclear reactions in carbon, Mylar, nickel, tin, and platinum targets [1, 2, 3]. Measurements of \(\sigma_{\text{tot}}^A\) were also attempted on \(E = 130 \pm 10\) keV antiprotons annihilating in carbon, palladium, and platinum target foils of sub-100 nm thicknesses [4, 5, 6]. These experiments were carried out at the Antiproton Decelerator (AD) of CERN using \(\Delta t = 50–120\) ns long pulsed beams that contained between \(N_p = 2 \times 10^5\) and \(5 \times 10^5\) antiprotons. The arrival of individual antiprotons at the target could not be resolved.

We instead determined the relative intensity and temporal structure of the beam by using acrylic Cherenkov detectors to measure the flux of secondary charged particles (mostly charged pions, muons, and electrons) that emerged from the simultaneous annihilations in the apparatus. These past experiments utilized fine-mesh photomultiplier tubes [7] which had signal responses that were highly linear to read out the Cherenkov radiators.

In this paper, we describe a different Cherenkov detector that consisted of an array of five lead fluoride crystals in the cubic phase (\(\beta\)-PbF\(_2\)) [8, 9, 10, 11] of size 30 mm \(\times\) 30 mm \(\times\) 160 mm. The arrival of antiproton pulses at the experimental target produced an intense flash of Cherenkov light in each crystal; this was measured by a reverse-type [12, 13, 14, 15, 16] avalanche photodiode (APD) of active area 10 mm \(\times\) 10 mm. These crystals are sensitive to both the charged secondary particles and \(\gamma\)-rays [17] that emerge from antiproton annihilations, and are expected to have a higher light yield compared to Cherenkov detectors based on acrylic radiators of the same size. Other advantages of the detector include its compact size and insensitivity to magnetic fields, which may allow its use in experiments involving magnetic Penning traps within the physics program of the AD [17]. The radiation-hard nature of the \(\beta\)-PbF\(_2\) crystals may allow their use in measuring high-intensity beams of electrons in laser spectroscopy experiments of metastable pionic helium atoms [18]. We compared the light yields of Cherenkov radiators made of \(\beta\)-PbF\(_2\), fused silica, acrylic, lead glass, and a lead-free, high-refractive index glass against antiproton annihilations. We also attempted to use p-i-n photodiodes [19] for the readout, but the waveform of the output signals contained a dominant background that arose from the nuclear counter effect (NCE) of secondary particles traversing the \(\sim 300\) \(\mu\)m thick depletion regions of these detectors [20, 21]. The relative size of the NCE was much smaller in reverse-type APD’s, because the maximum electronic gain occurred predominately for those electron-ion pairs that were generated in the thin p-type semiconductor layer that proceeded the p-n junction of high electric field where amplification took place [12, 13, 14, 15, 16, 21]. The detec-
2. Detector

2.1. Construction

The five $\beta$-PbF$_2$ crystals of size $30 \text{ mm} \times 30 \text{ mm} \times 160 \text{ mm}$ (see Fig. 1) were wrapped in two layers of a polyvinylidene fluoride membrane with 0.45 $\mu$m pores (Millipore Immobilon-P), which constituted a diffusive reflector. A silicon APD of active area $10 \text{ mm} \times 10 \text{ mm}$ (Hamamatsu Photonics S8664-1010, see Table 1) was attached to one end of each crystal. The five APD’s in the array were thermally anchored on a 200 mm long copper block using thermal paste (Electrolube HTCP). A two-terminal, temperature-to-voltage transducer (Analog Devices AD590MH) was also glued to the block using an epoxy adhesive that had a high thermal conductivity (Henkel Loctite Stycast 2650). This assembly was cooled to a temperature $T \sim 19^\circ\text{C}$ with a stability of $\pm 0.1^\circ\text{C}$, using two Peltier thermoelectric modules (Adaptive ET-03-10-13-RS) of size 30 mm $\times$ 15 mm and cooling power $\sim 6$ W that were regulated by a proportional–integral–differential controller (Thorlabs TED200C) and a separate 5 W direct current (DC) power.

Table 1: Specifications of the avalanche and $p$-$i$-$n$ photodiodes used in this study: their active areas, effective thicknesses against ionizing radiation, terminal capacitances, cutoff frequencies of the output signals, and wavelength ranges over which the photodiodes retain sensitivity.

| Photodiode | Area (mm$^2$) | Eff. thickness (μm) | Capacitance (pF) | Cutoff freq. (MHz) | Spect. response (nm) |
|------------|---------------|---------------------|------------------|-------------------|----------------------|
| S8664-1010 (APD) | 10×10          | ~ 5                 | 270              | ~11               | 320–1000              |
| S3204-08 ($p$-$i$-$n$) | 18×18          | 300                | 130              | 20                | 340–1100              |
| S3590-08 ($p$-$i$-$n$) | 10×10          | 300                | 40               | 40                | 340–1100              |

The advantages of $\beta$-PbF$_2$ crystals include a high refractive index ($n_r = 1.82$) and density ($\rho = 7.77$ g/cm$^3$), significant transmission at ultraviolet wavelengths $\lambda \sim 260$ nm, radiation hardness ($\sim 10^4$–$10^5$ rad) [8, 26], and a small radiation length ($\ell_r = 9.3$ mm) and Moliere radius ($M_r = 22$ mm). On the other hand, the light yield of $\beta$-PbF$_2$ is much smaller than those of scintillators such as lead tungstate (PbWO$_4$) and thallium activated cesium iodide (CsI(Tl)). For each MeV of energy deposited in a $\beta$-PbF$_2$ crystal, a photomultiplier coupled to it typically detects $\Gamma = 1.5$–1.9 photoelectrons [11]. It is difficult to grow large ($\ell \gg 200$ mm) crystals of high transparency and optical uniformity [27, 28, 29]. It was noted that when oxygen impurities were allowed to diffuse into the crystals during their growth, regions that consist of lead oxide, lead fluoro-oxide, or the opaque, orthorhombic phase of lead fluoride ($\alpha$-PbF$_2$) were formed. These appeared as scattering centers and inclusions that could reduce the collection efficiency of the Cherenkov light. It has also been reported that when exposed to a high-humidity environment, the surfaces of the crystals changed into a frosty-whitish appearance [28, 29].

Figure 1: (a) Layout of the Cherenkov detector hermetically sealed in an aluminum chamber. (b) Details of the $\beta$-PbF$_2$ radiator, photodiodes, copper block, printed circuit board (PCB), and Peltier thermoelectric modules.
resistor $R_f = 1 \, \text{k\Omega}$ which corresponded to a photocurrent-to-voltage conversion ratio $g \sim 10^3 \, \text{V/A}$ was chosen to provide the best dynamic range for measuring the Cherenkov signals with typical amplitudes of 20–40 mV. As the APD’s had a large terminal capacitance $C_d \sim 270 \, \text{pF}$, a compensating feedback capacitor $C_f = 22 \, \text{pF}$ was added to avoid excessive ringing and oscillation of the output signal, and obtain a flat frequency response with a -3dB corner frequency $f_r \sim \sqrt{f_c/2\pi R_f C_d} \sim 6 \, \text{MHz}$. For reading out the S3204-08 p-i-n photodiodes of $C_d \sim 130 \, \text{pF}$, the feedback elements were changed to values $R_f = 3 \, \text{k\Omega}$ and $C_f = 12 \, \text{pF}$ which provided the best compromise between a higher gain $g \sim 3 \times 10^5 \, \text{V/A}$, corner frequency $f_r \sim 9 \, \text{MHz}$, and the stability of the transimpedance preamplifier. For the smaller p-i-n photodiodes (S3590-08) of $C_d \sim 40 \, \text{pF}$, an operational amplifier (OPA843IDB) of larger gain bandwidth product $f_b = 800 \, \text{MHz}$ in conjunction with feedback values $R_f = 3 \, \text{k\Omega}$ and $C_f = 2 \, \text{pF}$ were used to obtain a -3dB corner frequency $f_r \sim 20 \, \text{MHz}$.

The output signals of the five transimpedance preamplifiers were summed using a resistor network, and amplified by a non-inverting follower of gain 2 which was based on a bipolar operational amplifier (Analog Devices AD829AR) with an input voltage noise $\sim 1.7 \, \text{nV/\sqrt{Hz}}$. This resulted in an output signal of typical amplitude $V = 200–400 \, \text{mV}$ into a 50 $\Omega$ impedance, which was superimposed on a DC offset. The signal was transmitted out of the chamber using a SMA-type coaxial vacuum feedthrough, and its analog waveform recorded by a digital oscilloscope of analog bandwidth $f = 4 \, \text{GHz}$, digital sampling rate $f_s = 10 \, \text{Gs/s}$, and a vertical resolution of 8 bits (Lecroy Waverunner 640Zi). The $\pm 5 \, \text{V}$ and $\pm 15 \, \text{V}$ DC power needed for the amplifiers were generated by four linear regulators (Linear Technology LT1965IDD and LT3015IDD) and passed through some electromagnetic interference filters (Murata BNX002). The linear regulators were supplied with source voltages that were adjusted slightly ($\sim 0.35 \, \text{V}$) above their regulated output voltages. This helped to minimize the heat dissipation in the chamber.

2.2. Cherenkov radiators

The $\beta$-PbF$_2$ crystals were grown using the Bridgman method and all surfaces polished by the Shanghai Institute of Ceramics, Chinese Academy of Sciences (SICCAS). The crystals were specified by the manufacturer to be without cracks or scratches longer than 10 mm and deeper than 2 mm, and no inclusions, scattering centers, or microcracks observable with the naked eye. Cherenkov radiators of the same size made of fused silica (CoorsTek T-4040), UV transparent grade acrylic plastic (Nitto Jushi Kogyo Co. Clarex S-0), high transmission grade lead glass (Schott AG SF57HTultra), and Ohara S-TIH53W glass were also manufactured (see Table 2). The last of these was a lead-free glass with a high refractive index $n_r \sim 1.8$, density $\rho = 3.5 \, \text{g/cm}^3$, and partial dispersion of Abbe number.
Table 2: Refractive indices, radiation lengths, and measured ultraviolet (UV) cutoff wavelengths of five types of Cherenkov radiator materials used in this work. The UV cutoff wavelengths are approximate values based on the measurements shown in Fig. 3.

| Radiator                  | Refractive index | Density (g/cm$^3$) | Radiation length (mm) | UV cutoff (nm) |
|---------------------------|------------------|--------------------|-----------------------|---------------|
| \(\beta\)-PbF$_2$ (lead fluoride) | 1.82             | 7.77               | 9.3                   | \(\sim 260\)  |
| T-4040 (fused silica)     | 1.49             | 2.2                | \(\sim 120\)         | \(< 190\)     |
| Clarex S-0 (acrylic)      | 1.46             | 1.18               | \(\sim 340\)         | \(\sim 320\)  |
| SF57HTultra (lead glass)  | 1.85             | 5.51               | 15                    | \(\sim 390\)  |
| S-TIH53W                  | 1.84             | 3.54               | \(\sim 390\)         | \(\sim 400\)  |

Figure 3: Longitudinal and transverse transmissions of Cherenkov radiators made of fused silica (T-4040), acrylic (Clarex S-0), lead glass (SF57HTultra), and lead free high refractive index glass (S-TIH53W) at wavelengths between \(\lambda = 300\) nm and 700 nm measured with a photospectrometer (see text).
Figure 4: (a) Four paths (indicated by T1–T4) parallel to the transverse axis of the β-PbF2 crystals where the optical transmissions were measured. (b) Transmissions at wavelengths between λ = 300 and 700 nm corresponding to each light path.

$T_1 \sim 80\%$ and $\sim 20\%$, respectively. The transverse values at λ = 520–700 nm and 380 nm were $T_1 \sim 82\%$ and $\sim 20\%$, respectively.

The UV transmission of the β-PbF2 crystals were lower compared to fused silica, but higher than the other three materials studied here [Figs. 3(i)–(j)]. Small, white scattering centres along the surfaces of the β-PbF2 crystals caused significant variations in the optical transmission: in one sample, transmissions of $T_1 \sim 74\%$, $\sim 35\%$, $\sim 32\%$, and $\sim 78\%$ were measured at the respective positions T1, T2, T3, and T4 [Fig. 4(b)]. The longitudinal transmission was typically $T_1 \sim 80\%$ at visible wavelengths λ = 400–700 nm, and $T_1 \sim 60\%$ at λ = 300 nm.

2.3. APD’s and p-i-n photodiodes

The S8664-1010 silicon APD’s [15,16] (Table 1) of active area 10 mm × 10 mm were previously used to read out CsI(Tl), BGO, and GSO(Ce) scintillators that emit at blue and green wavelengths [14, 30, 31]. The quantum efficiencies specified at wavelengths λ = 330 nm, 420 nm, and 600 nm were ε ≈ 45%, 70%, and 85%, respectively. The APD’s were of the so-called reverse type, where the p-n junction of high field in which multiplication takes place is typically located about $5 \, \mu m$ from the illuminated surface of the sensor [12, 13, 14, 15, 16]. Visible photons were absorbed and generated electron-hole pairs within the first few microns of the depletion region. These electrons were collected and underwent multiplication with the highest gain. Although charged particles, X-rays, and neutrons traversing the APD generated primary ion pairs over the entire width of the photodiode, only those pairs that originated in the thin p-type layer preceding the high-field p-n junction underwent high-gain multiplication. This lead to a small ($t_r < 6 \, \mu m$) effective thickness of the device with regards to the nuclear counting effect (NCE) against ionizing radiation, which was measured using a $^{90}Sr$ source [14].

The S3204-08 silicon p-i-n photodiode, on the other hand, had an active area of 18 mm × 18 mm, depletion layer thickness $d \approx 300 \, \mu m$, terminal capacitance $C_d \approx 130 \, pF$, and sensitivity at wavelengths between λ = 340 and 1100 nm with a maximum at λ = 960 nm (Table 1). Similar devices have been previously used for CsI(Tl) calorimeter readout [32, 33, 34, 35]. The S3509-08 p-i-n photodiode had a smaller active area 10 mm × 10 mm and capacitance $C_d \approx 40 \, pF$, and the highest signal cutoff frequency $f_c = 40 \, MHz$ among the detectors used here.

The signal linearity responses of the three photodiode and transimpedance preamplifier combinations were measured [33, 36] using the setup of Fig. 5(a). A light emitting diode (Thorlabs M450D3) produced a 100 ns long light pulse of emission wavelength $\lambda \approx 450 \, nm$, power $\sim 300 \, mW$, and emission angle $\theta = 120^\circ$. The light was attenuated using a pair of variable neutral density filter wheels and an iris, before being coupled into a 51 mm diameter integrating sphere (Thorlabs IS200) that had an internal surface reflectivity of 99%. The propagation direction and polarization of the light was thus randomized. Part of this light was extracted from the sphere through a pair of optical fiber bundles (Thorlabs BF20HSM0A01) that each consisted of 7 multimode optical fibers of core diameter $d \approx 550 \, \mu m$ and numerical aperture $N_A = 0.22$. The
fibers were made of fused silica with a high concentration of hydroxyl groups (OH). The intensity of the light emitted from each fiber bundle [indicated by A and B in Fig. 3(b)] was found to be equal to within $\sim 10\%$. The light was expanded using aspheric lenses of focal length $f_1 \sim 18$ mm (Thorlabs F280SMA-A) into a 8 mm diameter spot on the surface of one of the photodiodes. The other four photodiodes in the array were masked with a sheet of black rubber. The APD’s were biased at the nominal voltage $V_b = 380$ V. Measurements were carried out by irradiating the photodiode with, a): only the light beam emitted from bundle A [see Fig. 2(c)] corresponding to a measured signal intensity $S_A$ at the output of the readout circuit of Fig. 2, b): the light from bundle B corresponding to an intensity $S_B$, and c): simultaneous irradiation by the two beams corresponding to a measured signal intensity $S_{tot}$ [Fig. 2(b)]. Any saturation in the photodiode or preamplifier would lead to the $S_{tot}$ value being smaller than the expected sum $S_A + S_B$. In Fig. 6 the measured fraction $S_{tot}/(S_A + S_B)$ at various sums $S_A + S_B$ of the driver amplifier output (Fig. 2) in pC are shown for each photodiode type. Both $p$-i-n photodiode-amplifier combinations remained linear up to $S_A + S_B \sim 200$ pC. Any residual nonlinearity is primarily caused by the transimpedance and buffer amplifiers. The APD’s on the other hand saturated at a signal output of $> 40$ pC, presumably due to space-charge effects in the depletion region of the APD reducing the effective gain.

3. Measurements

3.1. Relative light yields of Cherenkov radiators

The schematic layout of the experimental setup used to measure the relative light yields $\Gamma$ of the Cherenkov radiators against antiproton annihilations are shown in Fig. 3. The AD provided a 200 ns long pulsed beam containing $N_p = (2 - 3) \times 10^7$ antiprotons with a kinetic energy $E = 5.3$ MeV and repetition rate $f \sim 0.01$ Hz. The beam was transported along an evacuated beamline. About 25% of the beam was decelerated to $E = 75$ keV by allowing the antiprotons to pass through a radiofrequency quadrupole decelerator (RFQD). A momentum analyzer beamline selected the $E = 75$ keV antiprotons and transported them to a cryogenic target chamber filled with helium gas. The antiprotons came to rest in the helium or metallic walls of the target chamber and underwent nuclear absorption and annihilation. Past experiments show (see Ref. 2 and references therein) that on average some $1.5 \pi^+$ mesons, $1.8 \pi^-$ mesons, and $2 \pi^0$ mesons emerge from a $\bar{p} + ^4$He annihilation, and that the momentum of most of the pions are distributed between $p = 0.1$ and $0.9$ GeV/c. The $\pi^0$ mesons preferentially decay into two $\gamma$ rays while still inside the target. The annihilations also lead to fission of the target nuclei, and the emission of fast and slow neutrons.

A single $\beta$-PbF$_2$ crystal was oriented so that either its short (indicated by position 1 in Fig. 2) or long (po-
The relative light yield yields of various Cherenkov radiators against antiproton annihilations measured by placing the detector at the two positions 1 (a) and 2 (b) indicated in Fig. 8. The radiators include lead fluoride (β-PbF$_2$), fused silica (T-4040), UV transparent acrylic (Clarex S-0), lead glass (SF57HT Ultra) and lead-free high refractive index glass (S-TIH53W). For the light yields measured at position 1, no significant differences were seen between detector configurations with (indicated by open circles) and without (filled circles) a silicone light coupler placed between the radiator and a fine-mesh photomultiplier, see text. The light yield of a plastic scintillator (EJ-200) is also shown.

Figure 9: (a) Black curve indicates the signal waveform of antiproton annihilations measured by reading out the β-PbF$_2$ radiators with APD’s as shown schematically in (b). It corresponds to the temporal profile of the 400 ns long pulsed antiproton beam. The green curve shows the NCE waveform measured by using a rubber sheet to prevent the Cherenkov light from reaching the APD as shown in (c). The red curve which is partially overlapping with the green one, corresponds to the waveform measured using only the APD without any radiator (d), see text.

The relative light yields Γ of the five radiators and plastic scintillator measured at position 1 are compared in Fig. 8(a). Each data point represents the average of measurements collected over 30 antiproton pulses, using three samples of each radiator type. The β-PbF$_2$ crystals showed the highest light yield that was a factor three larger than the Γ values of the fused silica and acrylic radiators. This is due to the short radiation length and high refractive index of β-PbF$_2$ that allowed the efficient detection of γ-rays and low-momentum pions. Primarily because of the low transparencies at short wavelengths, the lead glass and S-TIH53W radiators showed light yields that were factors of 5 and 10 smaller compared to β-PbF$_2$, respectively. No significant differences were seen between the Γ-values measured with (indicated by open circles) and without (filled circles) the silicone light coupler placed between the radiators and photomultiplier.

Fig. 8(b) shows the light yields measured with the five radiator types placed at position 2. The Γ-values of the fused silica and β-PbF$_2$ radiators are now approximately equal, despite the factor ~ 13 shorter radiation length of the latter material. This is believed to be due to the lower transparency of β-PbF$_2$ compared to fused silica which results in the absorption of a significant number of those UV Cherenkov photons that were produced in the part of the crystal closest to the experimental target, that prevent them from reaching the photomultiplier.

3.2. Nuclear counter effects

We next studied the nuclear counter effect (NCE) caused by secondary particles traversing the readout photodiodes. For this the β-PbF$_2$ array of Fig. 4 was positioned at a distance ~ 550 mm from the cryogenic helium target, with...
Figure 10: Signal waveforms of various detectors measuring antiproton annihilations in the helium target. Black curves represent the waveforms of the \( p-i-n \) photodiodes (a) S3509-08 and (b) S3204-08, and (c) the APD S8664-1010 coupled to a \( \beta \)-PbF\(_2\) radiator array. The NCE waveforms measured using only the photodiodes without the radiator are plotted using red curves that are superimposed on each spectrum. Signal and NCE waveforms of the light output of a plastic scintillator array read out by (d) S3509-08, (e) S3204-08, and (f) S8664-1010 photodiodes, see text.

the short axis of the crystals aligned towards the direction where the antiprotons annihilated. The AD provided a 400 ns long antiproton beam. The black curve of Fig. 9(a) shows the analog waveform of the signal obtained by reading out the \( \beta \)-PbF\(_2\) crystals using APD’s, and averaging the data accumulated over 10 consecutive arrivals of antiproton pulses at the target. A schematic drawing of one of the five crystal-APD connections in the array is shown in Fig. 9(b). The APD’s were biased at a voltage \( V_b = 380 \) V. The signal is a superposition of the flash of Cherenkov light in the crystal and the NCE, and shows the temporal profile of the beam. To roughly estimate the contribution of the NCE, the measurement was repeated with a black rubber sheet placed between the crystals and the APD’s to prevent the Cherenkov photons from reaching the APD’s [Fig. 9(c)]. The measured waveform [indicated by the green curve of Fig. 9(a)] shows that \( \sim 15\% \) of the detector signal arises from the NCE. The measurement was repeated with the \( \beta \)-PbF\(_2\) crystals removed from the detector. No significant change [red curve of Fig. 9(a)] was seen compared to the measurement with the rubber sheet. This indicates that the effect of the crystals shielding the APD’s from secondary particle hits was relatively small under the geometric layout of the experiment.

We next repeated the measurements by using the S3509-08 and S3204-08 \( p-i-n \) photodiodes as well as the APD’s to read out the five \( \beta \)-PbF\(_2\) crystals. The resulting waveforms are shown using black curves in Figs. 10(a)–(c). The pulse duration of the antiproton beam was reduced to \( \Delta t \sim 200 \) ns during these measurements. Each waveform represents the average of data collected from five antiproton pulses. The signal was normalized against the intensity of the antiproton beam which was measured using a separate acrylic Cherenkov detector read out by a fine-mesh photomultiplier tube. The NCE waveforms of each photodiode type measured by removing the \( \beta \)-PbF\(_2\) crystals are shown superimposed using red curves. The fact that the amplitudes of the \( p-i-n \) photodiode waveforms measured with and without the crystals are similar shows that most of the detector signal arises from the NCE. This agrees with the results of Monte-Carlo simulations [40] that indicate that each pion hit on a \( p-i-n \) photodiode predominantly produced \( > 20000 \) ion-electron pairs, compared to an estimated few hundred photoelectrons collected per hit on the Cherenkov radiator. The amplitude of the NCE waveform was proportional to the number of antiproton annihilations. The NCE effectively restricted the sensitive volume of the detector against charged pion and \( \gamma \)-ray hits.
to the $\sim 0.3$–0.5 cm$^3$ depletion regions in the photodiodes, instead of the full 720 cm$^3$ volume of the $\beta$-PbF$_2$ crystal array. The measurements of the antiproton annihilations were repeated using the EJ-200 plastic scintillator array. The signal waveforms of the scintillators read out by the three types of photodiodes are plotted in Figs. 10(d)–(f) using black curves. In the case of the $p$-$i$-$n$ photodiode, the NCE contribution [red curves of Figs. 10(d)–(e)] corresponded to $\sim 25\%$ of the total signal.

Fig. 11 shows the relative intensities of the APD signals against antiproton annihilations, measured at bias voltages between $V_b = 50$ V and 400 V. Each data point corresponds to the average of data collected from five antiproton pulses, which were normalized against the intensity of the antiproton beam measured using the acrylic Cherenkov detector. Measurements were carried out with (indicated by closed circles) and without (open circles) a $\beta$-PbF$_2$ radiator crystal coupled to the APD. At low bias voltages $V_b = 50$ V which corresponded to an APD gain near unity, the NCE constituted $> 60\%$ of the total signal. At higher bias $V_b = 380$ V corresponding to a APD gain $g \geq 80$, the relative intensity of the NCE was reduced to $\sim 15\%$ of the Cherenkov detector signal as mentioned above. A similar tendency of smaller relative NCE at higher gain was seen for APD’s reading out plastic scintillators (indicated in Fig. 11 by triangles), though some saturation in the signal was seen at $V_b \geq 320$ V. At a bias $V_b = 380$ V, the NCE corresponded to $\sim 2\%$ of the total signal, as shown in the signal waveforms of Fig. 10(f).

3.3. Antiproton beam intensity

Fig. 12(a) shows the relative intensities of 205 antiproton pulses that were decelerated by the RFQD to energy $E = 75$ keV over a 8 h period, measured using the $\beta$-PbF$_2$ Cherenkov detector array read out by APD’s (indicated by filled circles). A bias voltage $V_b = 380$ V was used. We simultaneously measured the response of the acrylic Cherenkov detector read out by a fine-mesh photomultiplier (filled squares), which is known to be highly linear at these beam intensities [7]. The shot-to-shot fluctuations seen here were primarily caused by variations in the number of antiprotons that were created in the production target of the AD. The correlation between the intensity measurements made by the two detectors [Fig. 12(b)] indicates that the linearity of the $\beta$-PbF$_2$ Cherenkov detector array is better than 5%. The residual nonlinearity is assumed to be mostly due to the contribution of the NCE and the response of the APD at high light intensities. Time- and temperature-dependent shifts in the APD gain were estimated to be of order $\sim 2\%$.

Fig. 13 shows the layout of an experiment [3] employing...
In conclusion, we have constructed a Cherenkov detector consisting of an array of five $\beta$-PbF$_2$ crystals of size $30 \text{ mm} \times 30 \text{ mm} \times 160 \text{ mm}$ read out by APD’s. The detector was used to measure the flux of secondary particles (mostly charged pions and $\gamma$ rays) emerging from the annihilations of high-intensity antiproton beams. When the radiators were positioned so that the majority of the secondary particles entered the radiator in the direction parallel to its short axis, the light yield of the $\beta$-PbF$_2$ crystals measured with a bialkali photomultiplier tube was a factor $>2$-$3$ higher compared to acrylic and glass radiators of the same size. When the secondary particles traversed the long axis of the radiators, however, the light yields of the $\beta$-PbF$_2$ and fused silica radiators became approximately equal. This is presumably caused by the lower UV transmission of $\beta$-PbF$_2$ compared to fused silica. Cherenkov radiators read out using $p$-$i$-$n$ photodiodes showed output signals that mostly consisted of the contribution from the nuclear counter effect (NCE) of secondary particles striking the photodiodes. APD’s were less affected by the NCE, so that its contribution in the case of $\beta$-PbF$_2$ readout was $\sim 15\%$ of the total signal in the experimental setup used by us. The $p$-$i$-$n$ photodiode and APD readout of plastic scintillators showed that the NCE contribution was $\sim 25\%$ and $\sim 2\%$ for the two photodiode cases, respectively. We used the $\beta$-PbF$_2$ Cherenkov radiators read out by APD’s in a recent measurement to determine the cross section of antiprotons with kinetic energy $E = 5.3$ MeV annihilating in carbon targets.

The authors are grateful to the ASACUSA collaboration and the proton synchrotron and Antiproton Decelerator operation teams of CERN. This work was supported by the Max-Planck-Gesellschaft.

References

[1] A. Bianconi et al., Measurement of the antiproton-nucleus annihilation cross section at 5.3 MeV, Phys. Lett. B 704 (2011) 461.
[2] M. Corradini et al., Experimental apparatus for annihilation cross-section measurements of low energy antiprotons, Nucl. Instrum. Meth. A 711 (2013) 12.
[3] H. Aghai-Khozani et al., Measurement of the antiproton-nucleus annihilation cross-section at low energy, Nucl. Phys. A 970 (2018) 366.
[4] H. Aghai-Khozani et al., First experimental detection of antiproton in-flight annihilation on nuclei at $\sim 130 \text{ keV}$, Eur. Phys. J. Plus 127 (2012) 125.
[5] A. Sóter et al., Segmented scintillation detectors with silicon photomultiplier readout for measuring antiproton annihilations, Rev. Sci. Instrum. 85 (2014) 023302.
[6] K. Todoroki et al., Instrumentation for measurement of in-flight annihilations of 130 keV antiprotons on thin target foils, Nucl. Instrum. Meth. A 835 (2016) 110.
[7] M. Hori, K. Yamashita, R.S. Hayano, T. Yamazaki, Analog Cherenkov detectors used in laser spectroscopy experiments on antiprotonic helium, Nucl. Instrum. Meth. A 496 (2003) 102.

[8] D.F. Anderson et al., Lead fluoride: An ultra-compact Cherenkov radiator for em calorimetry, Nucl. Instrum. Meth. A 290 (1990) 385.

[9] C.L. Woody et al., A study on the use of lead fluoride for electromagnetic calorimetry, IEEE Trans. Nucl. Science 40 (1993) 546.

[10] R.D. Appuhn et al., Electromagnetic calorimetry with lead fluoride crystals, Nucl. Instrum. Meth. A 350 (1994) 208.

[11] P. Achenbach et al., Measurements and simulations of Cherenkov light in lead fluoride crystals, Nucl. Instrum. Meth. A 465 (2001) 318.

[12] Th. Kirn et al., Properties of the most recent Hamamatsu avalanche photodiode, Nucl. Instrum. Meth. A 387 (1997) 199.

[13] R. Lecoma et al., Radiation detection measurements with a new "buried junction" silicon avalanche photodiode, Nucl. Instrum. Meth. A 423 (1999) 92.

[14] K. Dieters et al., Properties of the most recent avalanche photodiodes for the CMS electromagnetic calorimeter, Nucl. Instrum. Meth. A 442 (2000) 193.

[15] J. Kataoka et al., Recent progress of avalanche photodiodes in high-resolution X-rays and γ-rays detection, Nucl. Instrum. Meth. A 541 (2005) 398.

[16] T. Igaawa et al., Study of large area Hamamatsu avalanche photodiode in a γ-ray scintillation detector, Nucl. Instrum. Meth. A 538 (2005) 640.

[17] M. Hori, J. Walz, Physics at CERN's Antiproton Decelerator, Prog. Part. Nucl. Phys. 72 (2013) 206.

[18] M. Hori, A. Sotér, V.I. Korobov, Proposed method for laser spectroscopy of pionic helium atoms to determine the charged-pion mass, Nucl. Instrum. Meth. A 465 (2001) 144.

[19] Y. Hosono, Sjafruddin, T. Iguchi, M. Nakazawa, Fast neutron detector using PIN-type silicon photodiode, Nucl. Instrum. Meth. A 361 (1995) 554.

[20] A. Satpathy et al., Nuclear counter effect of silicon PIN photodiode used in CsI(Tl) calorimeter, Nucl. Instrum. Meth. A 391 (1997) 423.

[21] R. Mao, L. Zhang, R-Y. Zhu, LSO/LYSO crystals for future HEP experiments, J. Phys.: Conf. Ser. 293 (2011) 012004.

[22] S. Baunack et al., Measurement of strange quark contributions to the vector form factors of the proton at $Q^2 = 0.22 \text{ (GeV/c)^2}$, Phys. Rev. Lett. 102 (2009) 151803.

[23] A.T. Fienberg et al., Studies of an array of PbF$_2$ Cherenkov crystals with large-area SiPM readout, Nucl. Instrum. Meth. A 783 (2015) 12.

[24] J. Kaspar et al., Design and performance of SiPM-based readout of PbF$_2$ crystals for high-rate, precision timing applications, JINST 12 (2017) P01009.

[25] D.B. Cassidy, A.P. Mills Jr., A fast detector for single-shot positron annihilation lifetime spectroscopy, Nucl. Instrum. Meth. A 580 (2007) 1338.

[26] M. Kobayashi et al., A new heavy and radiation-hard Cherenkov radiator based on PbWO$_4$, Nucl. Instrum. Meth. A 459 (2001) 482.

[27] P. Achenbach, Observation of scattering and absorption centers in lead fluoride crystals, IEEE Trans. Nucl. Science 48 (2001) 144.

[28] G. Ren, D. Shen, S. Wang, and Z. Yin, Structural defects and characteristics of lead fluoride (PbF$_2$) crystals grown by non-vacuum Bridgman method, J. Crystal Growth 243 (2002) 539.

[29] G. Ren, D. Qun, Z. Li, and D. Shen, Transmission loss of lead fluoride crystals induced by oxygen contamination, J. Crystal Growth 247 (2003) 141.

[30] X. Jiu et al., Study of a pure CsI crystal readout by APD for Belle II end cap ECL upgrade, Nucl. Instrum. Meth. A 824 (2016) 691.

[31] Y. Kuno (COMET Collaboration), A search for muon-to-electron conversion at J-PARC: the COMET experiment, Prog. Theor. Exp. Phys. 2013 (2013) 022C01.

[32] H. Ikeda et al., A detailed test of the CsI(Tl) calorimeter for BELLE with photon beams of energy between 20 MeV and 5.4 GeV, Nucl. Instrum. Meth. A 441 (2000) 401.

[33] D.V. Dementyev et al., CsI(Tl) photon detector with PIN photodiode readout for a $K_{\mu3}$ T-violation experiment, Nucl. Instrum. Meth. A 440 (2000) 151.

[34] B. Aubert et al., The BABAR detector, Nucl. Instrum. Meth. A 479 (2002) 1.

[35] M. Ablikim et al., Design and construction of the BESIII detector, Nucl. Instrum. Meth. A 614 (2010) 345.

[36] M. Hori et al., Two-photon laser spectroscopy of antiprotonic helium and the antiproton-to-electron mass ratio, Nature 475 (2011) 484.

[37] M. Hori et al., Buffer-gas cooling of antiprotonic helium to 1.5 to 1.7 K, and antiproton-to-electron mass ratio, Science 354 (2016) 610.

[38] W. Budde, Multidecade linearity measurements on Si photodiodes, Appl. Opt. 18 (1979) 1555.

[39] K.D. Miehen and K.L. Eckel, Spectrophotometer linearity testing using the double-aperture method, Appl. Opt. 11 (1972) 2294.

[40] S. Agostinelli et al., Geant4 – a simulation toolkit, Nucl. Instrum. Meth. A 506 (2003) 250.