PHOTON DETECTORS FOR THE 21st CENTURY

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Abstract

The detection of photons over a very broad energy range is a challenging task in numerous fields of basic and applied research. We review here some techniques that have the potential of becoming the leading tools for photon detection in the next decades. The review covers gaseous detectors, hybrid detectors, solid state and superconducting devices.

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I. Introduction

The detection of light has fascinated man since early antiquity. Since his appearance on earth man has employed his own photon imaging detector- the eye. It is an extremely sensitive and highly pixelized device, equipped with remarkable data acquisition and analysis systems. The eye has about 160 million photosensors, as small as $2 \times 2 \mu\text{m}^2$ each, and a detection threshold of the order of 2500 photons/cm² [1]. In addition, it has a very good spectral resolution, namely the ability of colour separation. To improve the quality of vision, man inserted optical elements between the object and his "personal" detector. It is interesting to note that early experiments of gamma coincidence were carried out by Geiger, Rutherford and their colleagues, employing the eye. Two observers were looking through optical elements into two independent phosphor screens, irradiated by a gamma source, detecting events simultaneously scintillating in the dark [2].

To memorize images, man invented photographic plates. These were found later to be sensitive not only to visible light but to x-ray photons and charged particles. Photographic emulsions are still in use, mostly in photography and radiography, where they provide very high localization resolutions. However, the general tendency is towards real-time digital apparatus and photographic films will slowly disappear.

Advances in science and technology, particularly in the present century, have given rise to new dimensions to the field of photon detection and imaging. Motivated by the thirst to look further into the sky, deeper into matter and into his own body (Fig. 1), man has been inventing most sophisticated apparatus of impressive complexity and size, capable of detecting photons over a very broad energy range: from eV to TeV.

The guiding lines in most developments in photon detectors are efficiency (often to single photons), localization accuracy, energy resolution, time response, rate capability, long term stability, size etc. This is the place to note that the detectors may operate in two different modes: in pulse counting, detecting each photon separately, and in current integration, detecting several photons impinging on a detector pixel over a given time window.

The pulse counting mode provides time-resolved on-line information which permits the measuring of rapidly varying dynamic processes. The measured intensity obeys Poisson statistics and its dynamic range is limited by the memory size of the readout

system. Detectors operating in this mode are subject to some counting rate limitations, due to the detection mechanism and to the electronic circuitry.

Integrating detectors are either slow real-time devices, e.g., CCDs where the signal is proportional to the number of photons per time interval, or devices providing a static image analyzed off-line, e.g., photographic emulsions or phosphor imagers [3]. This mode is characterized by a significant integration of noise and therefore presents worse signal-to-noise characteristics. On the other hand images can be recorded with no rate limitations, provided no saturation occurs.

It should be noted that photon counting detectors are mostly employed in particle, nuclear and plasma physics while integrating devices are generally employed for various light imaging purposes, x-ray diffraction, and radiographic systems for medical and industrial imaging and safety inspection.

This conference will provide a glance into a large spectrum of the most advanced photon detectors of both categories, employed over a variety of fields. I will review here some of the detector techniques which I believe will play an important role in the next decades. I will divide this review into four groups of devices:

- photon detectors based on gas ionization and multiplication.
- hybrid detectors, combining a solid photon convertor and gas or vacuum electron multipliers.
- solid state photon detectors
- superconductive detectors.

II. Gaseous detectors

Detectors based on photoconversion and charge multiplication in gas, often over very large sensitive areas, have played an important role in photon imaging and I believe they will attract attention in the future as well, since no other technology can compete when very large detection areas are required.

In the field of x-ray imaging, in diffraction experiments or in radiography, gaseous detectors have some advantages over photographic emulsions. They provide real-time digital images of high contrast and despite somewhat lower resolution they offer a linear response in intensity and high detection efficiency. This allows to considerably reduce the

radiation dose to patients in the case of medical radiography [4] or to efficiently subtract images, taken at two photon energies close to the absorption edge of contrast agents, i.e., in transvenous coronary angiography [5]. Such instruments already play an important role in real medical diagnostics (Fig. 2).

More recently developed gaseous detectors, Microstrip Gas Chambers [MSGCs] [6] and Micro Gap Chambers [MGCs] [7] may become useful instruments for x-ray photon imaging. Instead of delicate amplifying wires, the multiplication in these devices occurs on very thin strip electrodes printed on insulator substrates. The thin strips can be replaced by arrays of very small anode pads and cathode rings, in so-called Microdot chambers [8], providing intrinsic 2D detection structures (Fig. 3). There have been numerous developments in this field, motivated by the possibility of reaching high localization resolutions and under radiation flux superior by two orders of magnitude ($> \text{MHz/mm}^2$) compared to that of wire chambers [9,10]. This results from the basic multiplication mechanism, in which ions are rapidly removed, under very high electric fields and over very short anode-cathode distance, from the avalanche region. To get sufficient detection efficiency for x-rays, such detectors which have a very narrow sensitive gap, should operate at high pressure of xenon [4] or with liquid xenon [11]. This improves localization resolution as well, due to a shorter range of photoelectrons and to the narrow gap that can be maintained, which reduces parallax errors under inclined incidence. It should be noted that x-ray imaging detectors of this type are already successfully employed for some space applications [12].

The weak point of these devices is related to the fact that the substrate on which anode and cathode strips are deposited (MSGC), or the insulator separating anode and cathode strips (MGC) suffer upcharging phenomena due to ion accumulation. A recent development aiming to solve that problem is the MICROME GAS detector [13]. Here, only thin anode amplifying strips are deposited on an insulator; avalanche ions are collected by a thin mesh placed at a few tens of microns above the strip electrode (Fig. 4). The authors claim a stable high gain operation, free of electrode charging up.

Gaseous detectors will continue to play a very important role in UV-photon imaging. A variety of wire chambers filled with photosensitive gases like TMAE (tetraakis (dimethylamine) ethylene) or TEA (Triethylamine) efficiently detect and localize with a

sub-millimeter resolution single UV photons, mostly in apparatus developed for relativistic particle identification by Cherenkov Ring Imaging [14]. Detectors covering sensitive areas of several square meters are currently operating in Particle Physics experiments [15]. TMAE-field UV imaging wire chambers are also employed for recording Gamma-induced light from BaF₂ crystals in a small PET camera [16].

A rather new and unconventional development is an instrument for detecting ultrasoft x-rays, in the energy range below 1 keV. It is based on counting the ionization electrons deposited by the absorbed photon in a low pressure gas volume [17]. Diffusion under low electric field causes the primary electron clusters to expand, resulting in electron trails where each electron is individually multiplied and counted. The number of electrons and the trail length, combined with a detailed simulation of the detector response, provide an efficient means for the precise quantitative identification of complex low-energy x-ray spectra, down to 100 eV (Be line) (Fig. 5). These room-temperature large area devices may have considerable interest for low-Z elemental analysis, even at very low element concentrations, in PIXE and electron microscopy as recently demonstrated [18].

III. Hybrid photon detectors

Hybrid detectors combine a solid radiation convertor with a multiplier that amplifies and detects charges, radiation-induced in the convertor. The multiplication may occur in vacuum or in gas.

III.a. Gaseous hybrid devices

A drawback of gaseous photon detectors is their relatively thick sensitive volume, which affects both the time and localization resolutions. Electrons following photon conversion at a given detector depth have to drift towards the multiplication element. The drift process introduces considerable time jitter, that can reach tens to hundreds of ns depending on the detector type and geometry, and causes the electrons to diffuse, affecting the localization accuracy. The localization is also affected by the photoelectron range in the gas, in the case of x-ray detection; in the case of energetic x-rays this becomes more serious. Here the detection efficiency is affected as well, unless large conversion

volumes are used, which causes serious parallax errors for inclined photon incidence.

Following some early ideas of solid Gamma converters coupled to wire chambers [19,20], EUROP SCAN came out with large area x-ray radiography scanning detectors (SYCOSCAN) combining high-Z tilted convertor foils, emitting energetic photoelectrons, detected by multiwire proportional chambers [21]. The photoelectron range in the gas affects the localization resolution but is not much of a problem when inspecting very large objects. Detectors of this type with 2 mm resolution were recently installed at the new French-British tunnel under la Manche, at Le Havre port and Roissy airport, for track and cargo inspection (Fig. 6).

Better localization resolution is obtained in detectors employing converters emitting multiple low energy (eV) x-ray-induced secondary electrons from the convertor surface[22]. This can be achieved using CsI converters or metal converters coated with CsI, as proposed for example for thermal neutron imaging [23]. Surface emission, even of higher energy electrons, followed by direct multiplication close to the convertor surface, guarantee excellent parallax-free localization and timing properties (Fig. 7). High gain ($>10^7$) and rate capabilities of the order of a MHz/mm² are attainable in two-stage multiplication geometries, under low gas pressure or in atmospheric pressure helium-rich mixtures [24]. 2D x-ray imaging detectors of this type could be considered as rather unique tools for time-resolved studies of fast evolving phenomena, on a nanosecond or even shorter scale. They could play, for example, an important role in protein crystallography, where the sample properties evolve under intense irradiation [25] (Fig. 8). Applications in radiography are possible as well [26].

Solid CsI converters combined with gaseous electron multipliers provide an effective solution for fast imaging of single UV photons [27]. The principle of detection is the same as the one discussed above for x-rays. CsI provides high quantum efficiency in the UV, typically 30% at 170 nm [28]. Large area CsI-based multiwire chambers already operate at the CERN-SPS relativistic heavy ion experiment NA44 [29], following intensive research in the field of UV-photon detectors for RICH, within the CERN RD-26 collaboration [30,31] (Fig. 9). Large arrays of such devices are planned for the future CERN-LHC ALICE experiment. Other experiments like HADES (GSI) and COMPASS(CERN) will also employ RICH detectors based on this technique. UV-photon

detectors based on CsI photocathodes coupled to MSGCs [32,33] and to MGCs [34] were also proposed. They are so far limited in size but present some advantages over wire chambers: for equal gain one can reach an order of magnitude or more of larger fast signals, due to the fast mechanism of ion removal under high fields [32]. Also, the photocathode may suffer considerably smaller damage by ion sputtering when placed above the strip structure, due to ion preferential collection at the cathode strips [32].

Among more recent attempts to develop robust UV photocathodes, stable in air and under gas multiplication, one should note thin CVD diamond films [35]. The quantum efficiency of these "solar-blind" photocathodes is rather low, at best 6% at 140 nm (Fig. 10), but this could possibly be improved by proper doping or surface treatment. Also interesting are the attempts to develop gaseous imaging photomultipliers for visible photons [36,37]. Recent experiments to protect photocathodes with very thin dielectric films [38,39] resulted in some successful results. The films should be thin, to transmit photons and photoelectrons, but on the other hand, opaque to oxygen, water vapour and other impurities. It was found for example that 150 Å thick NaI films could protect Cs₃Sb photocathodes against 5 min of exposure to 150 Torr of oxygen (equivalent to one atmosphere of air) [39] (Fig. 11). A better protection performance was very recently demonstrated by thin-film coating of K₂CsSb (bialkali) photocathodes. Higher stability in contact with oxygen of the coated photocathode was obtained, with QE values reaching 5% around 350 nm [40]. This should be considered as a remarkable result, allowing easy handling and manipulation of photocathodes under glove-box conditions. The thin film should in principle protect the photocathode against ion sputtering as well. Further attempts with a variety of protective films are under way [41]. If successful, this technique could make a breakthrough in the field of large area fast imaging devices for visible photons, capable of operation under very high counting rates.

III.b. Vacuum devices

In the last decade there has been steady progress in position sensitive photomultiplier tubes, equipped with various types of dynodes and anode readout geometries, capable of operation under high magnetic fields [42,43]. The principal motivation behind these developments has been readout of scintillating fibres but more

recently such devices were also proposed for imaging of Cherenkov light.

Progress in vacuum devices has also been reached in instruments coupling photoconvertors with vacuum multipliers based on MCPs. Large area imaging detectors of this type are mostly used in astronomy, in the ROSAT wide-field Camera. The bare or CsI-coated MCP electron multipliers are sensitive in the UV and in the X-ray photon range [44]. Position resolutions in the range of tens of microns can be reached with various electrode structures coupled to the MCP [45]. Recent progress has been made in vacuum electron multipliers made of stacks of very small spheres (the MSP, microsphere plate, Fig. 12) [46]. Here, high gains can be reached even in single MSP elements and the devices can operate also in a moderate vacuum, which is an advantage in some applications.

The most impressive and probably most promising device is based on the revival of an ancient idea [47] of vacuum operated Hybrid Photon Detectors (HPD) [48,49]. The HPD consists of a solid photocathode of which photoelectrons are accelerated at about 10 kV into a solid state detector. The detected signal pulse-height is proportional to the number of emitted photoelectrons. The device is sensitive even to single photoelectrons emitted from the photocathode. These devices which are now commercially available, are made in two electron acceleration geometries: proximity focussing and electrostatic focussing (Fig. 13). The latter permits having larger sensitive areas with smaller sensors, which can be of an advantage in some cases. HPDs have very low sensitivity to large magnetic fields.

Non-imaging HPDs are usually equipped with silicon PIN diodes, but there have also been devices using GaAs Schottky-barrier diodes, providing very fast response [50]. The "gain" of such tubes is of the order of 10^3 - 10^4 . Higher response can be obtained with HPDs equipped with avalanche photodiodes (APD) which provide an additional charge gain of 200, reaching total gains close to 10^6 [51]. The authors indeed described a position sensitive device with an array of 64 APDs.

Position-sensitive hybrid photodetectors are of considerable interest in a variety of fields and we can foresee that most of the future development efforts in HPDs will go in this direction. There have been two major developments in this respect: the Electron Bombarded CCD (EBCCD) [52], which provides very high resolution (~ 40 lp/mm) due to

the small CCD pixel size but at the expense of very low frame rates, and the Imaging Silicon Pixel Array (ISPA) - tube [53]. In the ISPA tube the electrons are accelerated into a silicon pixel array back-bonded to a fast readout system. At present, devices of this type have been operated with 1024 channel readout chips developed for the CERN LHC project, capable of running at close to MHz rates. The present pixel size is of $75 \times 500 \mu\text{m}$, which so far limits their resolution. When coupling an array of 0.6 mm square YAP scintillators to such an ISPA tube, resolutions of $300 \mu\text{m}$ FWHM were obtained with a ^{57}Co source (Fig. 14). This could be an interesting development for small-size, high resolution gamma cameras capable of operation at rates which are by orders of magnitude larger compared to the widespread technique of photon convertors coupled to CCDs. Position sensitive HPDs will certainly play an important role in Cherenkov Ring Imaging instrumentation developed for future particle physics experiments [54].

IV. Solid-state detectors

The considerable progress in micro-electronic technology, both in research institutions and in industry, has brought up a variety of new detector techniques. The trends are on one hand, the development of highly pixelized monolithic detector/readout systems, in silicon technology, but on the other hand different detection media are considered according to the photon energy.

In the visible range, apart from the well-known CCD cameras, two interesting detection techniques are to be noted, Visible Light Photon Counters (VLPC) [55] and Avalanche Photodiodes (APD) [56]. The VLPCs are very fast ($\text{tr} \simeq 0.1 \text{ ns}$) small area ($\sim 1 \text{ mm}$ in diameter) devices operated at 6°K , having high quantum efficiency of the order of 70-80% in the visible range. They can reach internal gains of $3\text{-}4 \cdot 10^4$. APDs operate at room temperature, they have a quantum efficiency of 80% at the 300-800 nm range and can reach dimensions $1\text{-}2 \text{ cm}^2$. The internal gain of commercially available devices is of the order of 10-100, but some authors report gains higher by an order of magnitude of more [57]. These authors demonstrated a 10% FWHM energy resolution for 6 keV x-rays directly impinging upon the APD and 14% FWHM resolution for a ^{57}Co source and a CsI(Tl) crystal coupled to the APD. Recent works report on metal resistive layer semiconductor (MRS) APDs, with built-in high field n^+ type inclusions, reaching gains of

the order of 10^5 or more, though still over very small area and with no energy resolution [58]. Their quantum efficiency is lower, limited by the avalanching probability, reaching at best values of 10-30% at $\lambda = 500\text{-}660\text{ nm}$.

Both VLPC and APD techniques are currently employed or projected in large scale particle physics experiments and one may foresee a massive use in other fields as well as in medical imaging, for example in PET [59]. They are immune to high magnetic fields and provide very fast response. In particular, the VLPC has the best known energy resolution in the visible range, compared to other existing vacuum, solid state or hybrid photon detectors [43]. The trend in APDs, which have the advantage of operating at room temperature, is to produce highly pixelized high gain devices, also in GaAs technology [60]; the latter provides faster response.

The greatest progress in solid state detectors has no doubt occurred in high resolution imaging devices for charged particles and x-rays; some of them with good energy resolution as well.

Detecting x-ray photons of energies above 10 keV involves efficiency problems when employing silicon, due to its long absorption length. Therefore, at higher energies other materials have been currently employed, such as Ge, GaAs, HgI_2 , CdTe and more recently CdZnTe [61,62]. For comparison, to reach 90% detection efficiency at 60 keV, one requires 32 mm of Si compared to about 2.6 mm of Ge or 0,5 mm of HgI_2 or CdTe. HgI_2 and CdZnTe detectors provide best energy resolution in the hard x-ray range.

Silicon strip detectors have been developed in a variety of geometries and technologies for the ultimate localization of relativistic particles. These devices, which provide localization resolutions down to 1 μm or less [63] with tiny strips running orthogonally, equip the majority of inner trackers in particle physics experiments. Considerable technological efforts have been made to miniaturize the readout chains of these detectors, a task which is rather complex regarding the very small interstrip distances. Such devices have been recently developed for 2D soft x-ray imaging [64]. An example of a micro-radiographic image obtained with a 300 μm thick detector equipped with 128 channel VIKING 3 chips is shown in Fig. 15. The image quality is good but the detection efficiency for the 60 keV x-rays employed here is very low.

Very good, sub-micron localization of 15 keV x-rays was demonstrated with a

commercial room-temperature operated CCD camera, using charge interpolation techniques [65]. However, in this technology, the detection efficiency and the counting rate are extremely low, which seriously limits its field of application. When cooled down to 160°K, CCDs provide excellent energy resolution, of 175 eV (FWHM) at 6 keV [66]. Combined with the good localization resolution this opens applications in astrophysics, in the soft x-ray range. The detection efficiency of such devices is a function of their depletion length, which in this technology is limited by impurities. At 1 and 10 keV, the efficiency is 50%, 55% and 5%, 35% for 7 μ m, 30 μ m depletion length respectively [66]. Very good energy resolutions in the soft x-ray range, were reached with CCDs having novel thin-poly gate structures and floating gate amplifiers [67]. These 30 μ m thick back-illuminated devices provide energy resolutions varying between 16 eV and 120 eV (FWHM) for 72 eV to 5.9 keV photons, respectively, at 160°K.

A breakthrough in this field is the new pn-CCD device [68], based on an idea close to that of Si drift chambers [69]. Charges released by a photon impinging through the backplane are transported via shift registers along the device in one direction. They are read out by a segmented anode (see fig. 16). This permits a much faster readout compared to standard CCDs. The pn-CCD provides a remarkable energy resolution, 119 eV (FWHM) at 6 keV, when cooled to 150°K (Fig. 17). This is superior to the resolution of a small area SiLi detectors often employed for soft x-ray spectroscopy. The 300 μ m deep depleted sensitive volume assures high efficiency for soft x-rays. A 12 CCD array of 1x3 cm² each, with 150x150 μ m² pixels has been designed for the XMM Satellite Mission planned for 1998. Though designed for space applications, one could foresee the spinoff of this technique in many other fields.

Another interesting Si-based device is the drift diode [70]. Charges released by x-ray photons impinging on the backplane of the detector, of a circular geometry, drift to a central anode of a very small size (Fig. 18). The on-chip electronics and the very small capacitance (100 fF) result in extremely low noise (ENC=9.6e⁻ and 22e⁻ at 223 and 300°K), for 300 μ m thick devices of 3.5 mm² in diameter. The energy resolution for 6 keV photons is 145 and 225 eV (FWHM) at 223 and 300°K, respectively. The detection efficiency of these drift diodes is 95% at 10 keV and 50% at 20 keV. They are produced in arrays, to provide localization and they can operate at detection rates reaching 1 MHz. Here also

many applications can be foreseen in the future, in the low energy range, down to few hundred eV [71].

A very interesting development is the Hybrid Pixel Detector developed by the CERN RD19 collaboration [72]. It consists of a pixelized detector chip mated to a readout chip by a bump-bonding technique (Fig. 19). This technique permits the bonding of any kind of detector material to the fast electronic chip. Devices of this type having 1024 channels of $75 \times 500 \mu\text{m}^2$ ($4.8 \times 8 \text{ mm}^2$) have been installed in the ISPA (HPD) discussed in Section III.b. They are based on the OMEGA chip that can record events at rates of 5 MHz. Newly developed 128 x 16 ch OMEGA3/LHC1 chips [73] of $50 \times 500 \mu\text{m}^2$ bump-bonded to a mating GaAs detector array, successfully recorded 60 keV x-ray images [74]. This technology is a beautiful example of a successful spinoff of particle physics. The fast read-out could be of considerable importance for radiographic applications, employing, if price permits, large arrays of such devices. Other silicon pixel array detectors with $150 \times 150 \mu\text{m}^2$ pixels were developed, having different techniques of readout chip bonding [75]. Such devices could have applications in x-ray imaging and visible photon localization in RICH when employed in HPDs. Very good localization resolution was measured with relativistic particles.

A large variety of position sensitive solid state detector arrays, with strip or pixel geometries, made of materials other than Si, are currently being developed for applications in digital radiography; some of them are commercially available. The reader is referred to some recent works on HgI_2 strip detectors [76], Ge PIN diode arrays [77] and CdZnTe linear (Fig. 20) [78] and pixel [79] array detectors. Very promising is the technique of position sensing of large single crystals of CdZnTe [80]. Resolutions of 1 mm (FWHM) over 1 cm^3 crystals were recently demonstrated at 122 keV. The energy resolution at 662 keV is 2% (FWHM). Of considerable importance are amorphous silicon pixel array x-ray detectors [81] and amorphous selenium devices [82] which can be produced in a large area by rather simple and economic techniques, with on-chip readout electronics.

I will close this chapter on solid state devices with an original and simple development of a high resolution imaging detector. It consists of a silicon strip array placed in such a way that the x-ray beam impinges upon its 0.5 mm thick side, in a

direction parallel to the 0.5 mm wide and 50 mm long strips [83]. Signals are recorded from the strips, namely from "pixels" of $0.5 \times 0.5 \text{ mm}^2$ area, 50 mm long. This geometry provides high detector efficiency for energetic x-rays. One can scan an object or employ a stack of such detector wafers. The resolution is a function of the wafer thickness and strip width. Impressive results were obtained with mammography phantoms, nicely resolving 0.3 mm in diameter objects with 20 keV x-rays at doses of 0.25 mGy. This development has been recently followed by proposing the use of stacks of CCD chips, for the detection of hard x-rays [84]. The CCD stack would be illuminated along its edge, similarly to the previously described Si-strip technique.

V. Superconductive photon detectors

Superconductive detectors have been developed over many years in many laboratories, principally aiming at resolving very small amounts of radiation deposited by various sources, mostly of cosmic origin. Detailed reviews on superconductive detectors and their applications can be found in refs. [85-88]. The idea in using superconductive detectors is to enhance sensitivity and resolution of the detected event, by increasing the amount of the deposited charge. Compared to about 20 eV in gas or to about 3 eV in a semiconductor required to produce an electron-ion or an electron-hole pair, in superconductive detectors we take advantage of the very small binding energy of Cooper pairs (meV) or the low energy of phonons at very low temperatures (1 μeV at 10 mK) to increase by several orders of magnitude the number of detectable charges, which leads to a lower detection threshold and better energy resolution. To avoid thermally induced background excitations, the detectors have to operate at very low temperatures.

There are several ways of exploiting various physical processes occurring in superconductive detectors, as reviewed in detail in the references [85-88]. The most popular detection principles are the following:

- using superconductive absorbers coupled to tunnel junctions; absorbed radiation causes break of Cooper-pairs and formation of quasiparticles that diffuse and get trapped in a tunnel junction, inducing detectable charge signals.
- using dielectric absorbers (single crystals) coupled to superconductive tunnel

junctions; phonons resulting from the absorbed energy in the crystal have energies exceeding the energy gap of the superconductor of the tunnel junction attached to the crystal; the energy can therefore be transferred to the tunnel junction via phonon-induced excitations of quasiparticles. The excess tunnel current is proportional to the energy absorbed in the crystal.

- using thermal detection; if the phonons are thermalized, the radiation interaction produces a temperature rise of an absorber that can be metal, a superconductive metal or a pure dielectric crystal. One attaches temperature sensors to the absorber, i.e., highly doped semiconductors whose resistance strongly varies with the temperature, or superconductive strip films. Here, very low temperatures are needed and compared to the previous devices that are very fast (ps range), the decay time of thermal detectors is in the ms range. So far these devices provide the best energy resolution.

As we deal with photon detectors, I'll discuss the progress and highlights in superconductive devices in this field.

Spectroscopy of low energy x-rays requires in some fields resolutions which are far superior to that of gas or semiconductor detectors described above, and even that of cooled pn drift diodes and CCDs. Even in the best noise-free devices the resolution is limited by Fano fluctuations, typically of a few tens of eV at 1 keV.

Very good resolutions in the soft x-ray range are needed for example to resolve spectra of diffuse interstellar media, to provide information on the composition and effective temperatures of electrons and ions. The 100 eV- 1 keV range is rich in spectral lines (Fig. 21) (K lines of light elements and higher order lines of heavier ones). Often good position sensitivity is needed, e.g., in investigations of the spatial structure of supernovae remnants.

High resolution devices could play an important role at intense Synchrotron Radiation experiments, for the identification of very dilute elements. This could be of prime importance in studies of biological samples that are particularly fragile when exposed to radiation. The high resolution would dramatically reduce exposure time.

Best results in terms of energy resolution were achieved so far in thermal microcalorimeters. Monolithic silicon pixelized devices of $0.5 \times 1 \text{ mm}^2$ pixel size, coated

with HgTe absorbers have been produced and operated at 60-80 mK [89]. Fig. 22 shows the pulse shape and energy spectrum of the Mn line. Fig. 23 shows the 5.9 keV Mn $K\alpha_1$ and Mn $K\alpha_2$ lines recorded on a single pixel, the deconvolution of which provides an energy resolution of 7.3 eV (FWHM), probably never reached before! A larger area pixel detector of this type was recently developed for rocket experiments [90]. The device has 36 pixels of 1 mm² on 12 μ m thick silicon coated with 1 μ m thick HgTe x-ray absorber, which provides a detection efficiency of 98% at 1 keV. The thermistors are ion-implanted into the silicon chip. The energy resolution of this device, operated at 60 mK, is 6-8 eV (FWHM) at 1.5 keV. A first flight of this device (June '96) on a sounding rocket provided very successful results [91]. Similar devices with thicker HgTe absorbers and smaller pixels (0.25 mm²) are planned for the ASTRO-E satellite mission, for x-ray spectroscopy at the 10 keV range. Predicted resolutions are of 10-15 eV (FWHM).

The presently reached energy resolution of superconductive tunnel junctions (STJ) is lower compared to that of thermal microcalorimeters, though progress is still possible. An energy resolution of a superconductor/insulator/superconductor (SIS) detector was recently reported to be of 29 eV (FWHM) at 6 keV. It was measured at 200 mK with a fast SQUID amplifier [92]. Various pixel arrays based on STJ have been proposed, to provide tools for ultrafast, high localization resolution x-ray spectroscopy [93]. Operation at repetition rates reaching GHz could be possible using fast (ps) superconductive Josephson junctions [93].

A remarkable potential application of superconductive detectors is the detection of UV and even of visible light. It has been very recently demonstrated that Nb/Al junctions provide a good way to spectrally resolve single photons, down to 500 nm ($\sim$ 2.5 eV), by measuring their pulse height [94,95]. The quantum efficiency is about 50%. Examples of photon spectra and the linear response in energy are given in Figs. 24,25. The energy resolution at 5 eV is of the order of 30% (FWHM), which is a remarkable fact that will certainly be exploited in some future practical applications.

VI. Concluding remarks

The field of photon detection is vast, increasingly demanding and ever growing. There have been numerous important developments over the past few decades in detectors based on photon interaction with gases, solids (also superconductors) and

liquids, followed by charge collection or multiplication by various internal or external mechanisms. The general trend is increasing localization, energy and time resolutions as well as the counting rate capability and detection efficiency. I have reviewed here some of the major recent techniques in this field, part of them still at early development stages, which I consider having good potential or convincing proofs for becoming the leading tools for the next century. I certainly omitted a few others, e.g., devices for the infra-red or for very energetic Gammas, and I apologise here to their inventors and to the reader. I described in most cases the principal properties of the various devices, intentionally refraining from deep comparative remarks involving complexity, cost, availability, facility of operation, lifetime etc. This should be left to the reader, who is referred to numerous original works and reviews.

The author is the W.P. Reuther Professor of Research in the peaceful use of atomic energy.

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Figure Captions

- Fig. 1 Three-dimensional reconstructed images recorded by x-ray Computerized Tomography with the ELSCINT CT Twin Flash Scanner, equipped with a double beam and detector array. The detectors are CdWO_4 scintillator arrays, coupled to silicon diodes. The images were taken in a "spiral mode" with iodine contrast agent. a) The spine, aorta, blood vessels and kidneys, taken in 2.5 mm slices; b) The main blood vessels in the skull, taken with 0,5 mm slices (courtesy of ELSCINT, Israel).
- Fig. 2 Intravenous angiogram of a patient taken with the NIKOS III ionization wire chamber. It shows images recorded at two energies (E_1 and E_2), above and below the iodine absorption edge and the result of the substraction image. Visible are the aorta (A), pulmonary veins (PV) and the right coronary artery (RCA). The latter is visible down to diameters of about 1 mm [5].
- Fig. 3 The MICRODOT chamber combining a gas ionization volume and an array of electrodes on an insulating substrate, shown in the figure. The multiplication occurs on the central dot, reaching values superior to 10^4 . The device provides high accuracy 2D localization, as the dot pitch is of 0.1-0.2 mm [8].
- Fig. 4 A schematic view of the MICROMEGAS gaseous imaging detector. Ionization electrons drift towards a very narrow amplification gap with thin parallel anode strips deposited on an insulating substrate. The device provides 1D localization and operates at high gains under large radiation flux [13].
- Fig. 5 Data from a large area gaseous detector for ultrasoft x-ray spectroscopy (down to 100 eV). a) A pulse-trail showing pulses originating of gas avalanches initiated by individual electrons deposited in a low density gas by very soft x-rays. The technique is based on counting the number of electrons (n), proportional to the deposited energy, deposited by the photon and the pulse-trail length (t); b) and c) show 2D (n,t) and 1D (n) spectra of light elements recorded in electron microscope. Advanced data analysis algorithms permit identification of very close and dilute x-ray lines [17,18].
- Fig. 6 A radiographic image of a boat taken with the SYCOSCAN x-ray inspection system at the port of le Havre. The scanning system is equipped with a gaseous

detector combining a metal radiation convertor and a wire chamber amplification and data recording system. The arrow shows a smuggled ivory art statue [21] (courtesy of EUROP SCAN).

- Fig. 7 The operation principle of the secondary electron emission radiation detector. x-rays converted in a thin cathode foil, induce the emission of several low-energy (eV) secondary electrons per incident photon. These are immediately multiplied at the high electric field in the gap close to the convertor, and further amplified in a wire chamber or another electron multiplier. The surface emission and multiplication result in good localization properties and fast (ns) response [22].
- Fig. 8 An example of an x-ray image recorded with the detector shown in fig. 7, representing small-angle scattering from collagen (rat tail). The image was recorded at an intense synchrotron radiation beam (at ESRF), during 20 sec, at 850 kHz [25].
- Fig. 9 A schematic view of a UV-photon detector for Ring Imaging Cherenkov applications, combining a CsI photocathode deposited on an array of small pad electrodes that constitute the cathode of a wire chamber. Particle-induced UV-photons in a Cherenkov radiator produce the ring patterns shown below, used for particle identification [30,31].
- Fig. 10 Examples of the absolute quantum efficiency of a CVD diamond film produced by the hot-filament technique and a diamond like carbon (DLC) film, produced by low energy ion implantation [35].
- Fig. 11 Results of the thin-film protection of the surface of visible photocathodes. The photocathodes were coated by thin dielectric films of different thicknesses and exposed to oxygen for successive periods of 5 min at each experimental point shown in the figure. While a bare Cs_3Sb photocathode totally decays at 10^{-5} torr, it suffers 50% decay only at 150 torr for a 151 Å thick NaI coating film [39].
- Fig. 12 The principle of operation of the microsphere plate electron multiplier and its multiplication characteristics.

- Fig. 13 Schematic views of the hybrid photon detectors (HPD) with proximity focussing geometry (a) and electrostatic focussing (b). Photoelectrons from a photocathode are accelerated in vacuum into a solid state detector; the latter can have imaging properties. The electrostatic focussing geometry permits large detection areas to be viewed with small solid state devices.
- Fig. 14 The principle of the small Gamma ray camera combining small YAP scintillators and an HPD tube equipped with a pixel array detector (the ISPA tube). Shown is a 2D image obtained with ^{57}Co through 0.25 mm diameter holes; the resolution is 0.3 mm [53].
- Fig. 15 Example of a micro-radiographic image of a small Ge diode, recorded with 60 keV x-rays in a double-sided silicon microstrip detector. The diameter of the thin wire at the centre of the diode is 50 μm , which is also the image pixel size; the image full size is 6.4 x 6.4 mm [64].
- Fig. 16 A schematic view of the pn-CCD x-ray imaging camera. Charges deposited in the 270 μm thick sensitive volume (by back-illumination of the device) are transferred in one dimension through shift registers towards a series of pickup anodes. The imaging device has fast readout and good energy resolution [68].
- Fig. 17 The energy response of the pn-CCD (shown in Fig. 16) for Mn x-rays. The resolution is 119 eV (FWHM) at 150°K [68].
- Fig. 18 The principle of operation of the silicon drift diode with integrated n-channel JFET; the gate of the transistor is connected to the collecting anode. Charges released by the back-illuminating x-rays are collected, after drift in the silicon, by the anode. The low capacitance (100 fF) assures low noise and high energy resolution. Large area devices can be formed by combining arrays of such diodes [70].
- Fig. 19 The principle of bump-bonding of the pixel detector array to its mated readout chip. The advantage of such a system is the flexibility in the detector array material choice [72].
- Fig. 20 A radiographic image of a laboratory clock, recorded with a 1D linear array of 32 pixels of CdZnTe sensors [78].
- Fig. 21 A comparison between the cosmic x-ray background recorded by the ROSAT gas

proportional chamber and predicted spectra of the same background employing state-of-the-art CCDs for the CUBIC experiment and microcalorimeters with 5 eV (FWHM) energy resolution. This demonstrates the considerable advantage of using superconductive detectors for astrophysics experiments [89].

Fig. 22 An example of a single x-ray induced pulse from a pixelized microcalorimeter and the energy spectrum of Mn $K\alpha$ and $K\beta$ lines, recorded at 80 mK [89].

Fig. 23 A spectrum of the Mn $K\alpha_1$ and $K\alpha_2$ lines recorded with a pixelized microcalorimeter, at 60 mK. The deconvoluted resolution of the detector, which is the world-record in x-ray detection, is 7.3 eV (FWHM) [89].

Fig. 24 Single photon spectra in the UV and the visible recorded with superconductive Nb/Al junction at 0.37°K. The energy resolution at 250 nm is of the order of 30% (FWHM); the quantum efficiency is about 50% [94].

Fig. 25 The remarkable linearity of the superconductive junction detector in the UV-to-visible range [95].

a)

b)

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

**Hidden at the back : an art statue smuggled in offence against
the Washington Convention ▼**

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Micro Sphere Plate

Fig. 12

a)

b)

Fig. 13

Fig. 14

Fig. 15

Fig. 16

Fig. 17

Fig. 18

Fig. 19

Fig. 20

Fig. 21

Fig. 22

Fig. 23

Fig. 24

Fig. 25