New trends in radiation imaging: CsI-based gaseous detectors

A. Breskin*
Department of Particle Physics
The Weizmann Institute of Science
76100 Rehovot, Israel

SW 9525

A new class of radiation imaging detectors is described. They combine thin solid convertors and gaseous electron multipliers. CsI or CsI-coated films provide an efficient means for UV, X-ray and thermal neutron conversion. The latter is followed by the emission of single photoelectrons or multiple secondary electrons in the eV range. The surface conversion and the electron multiplication close to the radiation impact location guarantee an accurate localization, fast response and low occupancy, regardless of the angle of incidence. A low gas pressure permits the operation at very intense radiation flux, with a low sensitivity to ionizing background. The article briefly reviews the new technique and its potential applications.

Presented at the Wire Chamber Conference, Vienna, February 1995.

To be published in Nuclear Instruments and Methods in Physics Research A.

*The Walter P. Reuther Professor of Research in the peaceful uses of atomic energy.

I. Introduction

Many fields of research involving the detection of radiation encounter serious limitations due to the physical limits of present detectors. In particular, the operation of gaseous wire-chambers, widely employed in many fields, is based on charge deposition in a gas volume, followed by a relatively slow (tens to hundreds of ns) electron collection and multiplication. This seriously affects the time and localization properties of these devices. It puts a limit on the repetition rates of wire chambers and therefore on their capability of operating under very high radiation flux. The latter is also limited by serious space charge effects.

We propose a novel class of radiation imaging devices which overcome many of these limitations. The detectors are based on the amplification and detection of radiation-induced secondary electrons from thin solid conversion foils, emitted into gas media¹⁻³). The convertors are selected according to the type and energy of the incident radiation.

The interaction of radiation with solids results in the creation of primary particles, which by a cascade of interactions in the solid induce the emission of low-energy secondary electrons. This secondary electron emission (SEE) is very effective in insulators, and particularly in alkali-halides, due to their large energy gap and small electron affinity^{4,5}). Electrons with energy smaller than the energy gap have a long mean free path in the solid; they experience very small energy losses due to a weak coupling with the phonons. Best known emitters are alkali-halides, in particular CsI, which typically emit several tens of secondary electrons upon the absorption of a few keV photon; this is by an order of magnitude more than in metals⁵).

The low energy (eV) secondary electrons are emitted into a gaseous imaging electron multiplier in which amplification is initiated at the conversion surface. The imaging electron multiplier can be preferably a two-stage avalanche chamber, shown in fig. 1, operating at low-pressure (10-20 Torr)⁶) and providing accurate localization of the surface emitted secondary electrons in a subnanosecond time scale⁷). This operation principle, by which the radiation interacts with the solid convertor and not with the detector gas, leads to a fast response induced by the surface emitted electrons, high-accuracy parallax-free

imaging and low sensitivity of the detector to ionizing background radiation. The low-pressure allows for an operation at very high radiation flux, due to a very reduced space-charge effect during the avalanche buildup. An alternative way of multiplying surface emitted electrons is based on a Microstrip Gas Chamber operated at low gas pressure^{8,9)}. A fast two-stage multiplication mode provides fast single electron-induced signals at gas gain $<10^5$.⁸⁾

The newly proposed detection technique may open new avenues in many fields of research, incorporating the imaging of UV-photons⁷⁾, X-rays²⁾, thermal neutrons¹⁰⁾ and charged particles¹¹⁾ as discussed below.

The present article provides a concise background to this new field and a selection of references of more complete works. Ref. 3 provides a more detailed review of the subject.

2. Principal applications

By a proper choice of the radiation convertor/emitter material, the detector shown in fig. 1 can be adapted to the imaging of various sources of radiation. As already mentioned above, CsI is a very good candidate in many fields. It has a very high quantum efficiency in the UV (140-220 nm) (fig. 2) which makes it a prime choice convertor in MCP-based vacuum photomultipliers¹²⁾, and gaseous photomultipliers⁷⁾. The latter were proposed for fast recording of photons emitted from scintillators and are presently intensively developed for single UV-photon localization in fast Ring Imaging Cherenkov detectors (Fig. 3)¹³⁻¹⁶⁾. CsI has also been known as an efficient soft X-ray convertor⁴⁾, a property intensively investigated in combination with gaseous electron multipliers^{2,17)}. We have proven the excellent imaging properties of ultrafast SEE-based X-ray detectors (Fig. 4), developed by us for static and time-resolved radiography and diffraction studies. Detectors of this type demonstrated their imaging properties under very high flux in protein crystallography, recently experienced at ESRF (Fig. 5)¹⁸⁾. "Hadron-blind" Transition Radiation (TRD) devices based on SEE X-ray detectors with a ns time resolution and low occupancy, are proposed for particle identification in future experiments in high energy physics¹⁹⁾. Recent simulation work proves their high

efficiency to ultrarelativistic electrons and very good hadron rejection properties²⁰⁾. High accuracy neutron imaging was recently demonstrated, using composite neutron convertors combining Gd or Li foils coated with thin CsI emissive films (Fig. 6)¹⁰⁾. Charged particles, following an interaction of a neutron with the convertor, induce a massive secondary electron emission into the detector gas, providing with good accuracy (~ 0.4 mm FWHM) the neutron impact location. The sensitivity of SEE-based detectors to relativistic particles is considerably increased using CsI-coated thin diamond films¹¹⁾.

3. Convertor modelling

Advances and successes in this new field of detectors, strongly rely on the understanding of the SEE and photoemission processes of the convertor.

A physical model was developed, describing the radiation-induced SEE process in alkali halides²¹⁻²⁴⁾. It is based on the microscopic formulation of all electron interactions in the solid. Monte Carlo simulations based on this model follow the primary and secondary electron transport in the solid and successfully reproduce existing experimental data for alkali halides. The model provides a tool for a deeper understanding of the SEE process, i.e. it gives the secondary electron cascade size²³⁾, energy²⁴⁾ and the yields²²⁾ of primary and secondary electrons as function of various physical parameters (convertor type and thickness, incident radiation type and energy, etc.) . This information is very valuable for detectors' design. The validity of the SEE model was experimentally proven in the fields of X-ray¹⁷⁾, particle²⁵⁾ and thermal neutron-induced¹⁰⁾ SEE from CsI. An important development is the modelling of UV-induced photoemission from CsI, which is very sensitive to the correct formulation of the interactions of very low energy electrons, in the sub eV range. Recent calculations remarkably reproduce the experimental quantum efficiency of reflective and semi-transparent CsI films²⁴⁾.

4. Basic properties of CsI

Basic studies of the electron emission process from CsI, mainly in the UV range, were carried out in vacuum and in gas by several groups¹³⁾. Recent studies revealed the

importance of surface electric fields, surface structure and electron backscattering in the gas. At very high electric fields, above 100 kV/cm, in vacuum, the surface potential (electron affinity) is modified, leading to an enhanced photoemission (Fig. 7), more pronounced at the longer photon wavelengths²⁶). An interesting consequence is the enhanced sensitivity of UV photocathodes to fast scintillators, like BaF₂²⁷) which is very important for fast γ -imaging applications. Photoemission into gas, under low electric fields, was shown to be strongly affected by electron backscattering, which is more pronounced in noble gases^{28,29}). A significant drop in the QE, as compared to the vacuum values, was measured for example in a charge collection mode (low electric field) in He-based mixtures, while in CH₄-based mixtures, the backscattering is negligible (Fig. 8). At higher electric fields, under gas multiplication, the effect of backscattering disappears and the QE resumes its vacuum value. These findings provide a way for the optimal choice of gas for SEE and photoemission detectors. Systematic studies of CsI evaporated films were carried out, involving laterally resolved surface properties³⁰) as well as the average quantum response³¹). It was shown that rather uniform deposition of polycrystalline films, with standard vacuum deposition, can be achieved by a proper choice of the substrate. Very good results have been obtained on Ni- and Ni/Au-coated printed circuit board substrates^{15,31}). On a microscopic scale of 3-30 μ m, the SEE and photoemission are highly inhomogeneous, and the electron yield reflects not only the granular structure but also some chemical variations. It was shown that the photoemission yield can be enhanced by annealing of the layer in vacuum under 60°C for several hours (Fig. 9), providing films which are rather stable to short exposures, of 15-30 minutes, to air^{31,32}). This is very important for the handling of detectors combining CsI convertors.

5. Summary

We have briefly discussed the principle of fast, high resolution radiation detectors, combining solid convertors and gaseous electron multipliers. CsI or CsI-coated films are convertors of choice for UV, X-ray and thermal neutron imaging. SEE-based detectors could considerably improve timing and localization properties of heavily ionizing particles. With some further developments they could be applied to the detection of relativistic charged particles under very high multiplicities and rates. Progress in understanding CsI

properties is important for further advances in this field. Several potential applications already exist in various fields of basic and applied research.

This work was supported by the Foundation Mordoh Mijan of Salonique, the Israel Academy of Sciences and Humanities, the US-Israel Binational Foundation, the Commission of the European Communities and by the Israel Ministry of Science and Arts.

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Figure Captions

- Fig. 1. The operation principle of a two-stage secondary emission detector. Incident radiation, converted in a thin solid CsI or CsI-coated film, induces the emission of single (UV-induced) or multiple low-energy secondary electrons. They start a multiplication process at the vicinity of the convertor surface and are further multiplied and localized in a second amplification stage.
- Fig. 2 The quantum efficiency (QE) of reflective CsI films measured at the Weizmann Institute (WI) and at Ecole Polytechnique (EP) [33]. The data are compared with that of Anderson et al. [34] and Seguinot et al. [35]. The QE of TMAE [36] is provided for comparison.
- Fig. 3. Single events of Cherenkov rings induced by 3 GeV/c pions in a proximity-focusing RICH. Photons from a C_6F_{14} radiator are converted in a CsI layer, deposited on a pad readout electrode of a MWPC [15]. The pad pattern shows the central particle cluster surrounded by single photoelectron clusters. The pad size is 8 x 8 mm².
- Fig. 4 Radiographic images of plastic-made syringe, ink-pen and a wrist-watch, obtained with the SEE X-ray detector shown in fig. 1, equipped with an Ag convertor. The images were obtained using a 15-30 kV X-ray generator.
- Fig. 5 Raw data of a) a crystallographic image of a protein (Seryl TRNA Synthetize from T. Thermophilus) and of b) small angle scattering from Collagen (from a rat tail), measured under very high X-ray flux with an SEE-based X-ray detector [18].
- Fig. 6 Comparative radiographic images of a small (25 mm in diameter) metal ball-bearing, made with thermal neutrons ($\lambda = 0.2$ nm) with a) a Polaroid Nr. 57 film preceded by a Li/ZnS convertor; b) a SEE detector equipped with a Li/CsI

converter. The images indicate clearly the presence (top) or the absence (bottom) of grease in the bearing.

Fig. 7 Relative increase of QE of CsI as a function of the square root of the surface electric field strength, in vacuum at 160 and 185 nm (a) and at >200 nm (b) [26].

Fig. 8 The ratio of the photocurrent from CsI, at 185 nm, in CH₄ and in He-and Ar-based gas mixtures at atmospheric pressure, to the photocurrent in vacuum (measured at the same absolute electric field values), as a function of the reduced electric field in gas. Notice that in the charge collection mode ($E/p < 4$ V/cm · Torr) the photocurrent in CH₄ (and CH₄-based mixtures not shown here) and in some Ar-based mixtures approaches that of vacuum. He-based mixtures would considerably reduce the QE of CsI [28,29].

Fig. 9 The results of the heat enhancement of the QE of CsI deposited on Ni-coated printed circuit board. The annealing process at 60°C, under vacuum for several hours, increases the QE to values which are close to those obtained by us with the best CsI layers deposited on polished stainless steel (SS).

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