CURRENT TRENDS IN IONIZING RADIATION DETECTION

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Ionizing radiation is a both a natural and man-made phenomena that plays a major role in contemporary applications. The detection of this radiation has evolved over the past several decades from simple observations to precise measurements in space, time, and energy, even in harsh environmental conditions. In this paper, we present a snapshot of the current state-of-the-art in radiation measurement technology, highlighting the major applications and detector developments.

KEYWORDS : Ionizing Radiation, Semiconductor Detector, Radiation Detection, Scintillator, Cryogenic Detector

1. INTRODUCTION

The discovery of radioactivity was also the birth of the field of radiation measurements. Over the ensuing century, the ability to sense radiation evolved from qualitative observations to precise measurements of its energy, intensity, and location, even as a function of time. The applications that influence the detector R&D have continued to demand more from the detector and analysis systems, and in this overview paper, we highlight the current directions in the continuing development of radiation measuring instruments. We begin by looking at the applications that are driving detector research today, and then focus on contemporary advances in the four primary detector categories: gas-filled detectors, scintillators and light conversion devices, semiconductors, and other miscellaneous detectors. Because of the remarkable breadth of this technology it is impossible to do service or even recognize all areas of development. For example, we cannot give sufficient attention to the remarkable advances in electronic readouts nor some of the hybrid devices that span multiple categories. Nevertheless, this gives us a place to start and we beg the reader's indulgence it we omit a detection technology of particular interest to their field.

2. APPLICATIONS THAT DRIVE RADIATION DETECTOR RESEARCH

2.1 Biotechnologies

Transmission radiography has likely been the largest user of radiation detectors. These systems range from simple transmission x-rays to more complex forms such as computed tomography with multiple radiation sources and detectors rapidly circling around the patient in a helical path. Traditionally, the use of film has been the primary detection modality in clinical settings. This multibillion-dollar market is ripe for transformation to digital radiography in which the film is replaced by a fast radiation detector, in the same way that optical cameras in the consumer market have evolved beyond film. Digital radiography systems offer the promise of a larger intensity range, better linearity between dose and signal, enhanced contrast, and perhaps most importantly, direct conversion to a digital signal at the point of detection [1].

The introduction of the bright light sources from synchrotrons has introduced severe demands in radiation detection, particularly at low (keV) energies where these devices operate. In this case, the inherent high-intensity of the source coupled with the need for very high spatial resolution places unparalleled demands on the detector designer. The resulting detectors need the ability to produce 3-D images of complex biological structures, such as a virus or ribosome. Furthermore, current studies (biocrystallography) are seeking to unravel the time-resolved changes in fundamental building blocks and are beginning to illuminate critical biological processes [1].

In the area of emission radiography, a radiopharmaceutical is administered that will follow a particular biological pathway. Measuring the resulting emission reveals the functioning of a particular organ. SPECT and PET remain commonly prescribed diagnostic procedures, although their popularity has likely waned with competition from non-radiation approaches such as stenography and magnetic resonance imaging. But for coronary studies, functional brain imaging, and small animal studies, emission radiography

serves as a primary tool. The key technology drivers are improved spatial resolution and increased efficiency for reduced dose to the patient. And in positron emission tomography the thrust is ever towards faster scintillators that enable combined PET and SPECT cameras. Autoradiography, another technique relying upon imaging the emission from an absorbed radioisotope (e.g., using tritium labeling) but on the microscopic level, continues to be an important tool for pathology researchers. The goal here is to replace their conventional films with digital radiation detectors and readouts [1].

In clinical radiotherapy, dosimetry is particularly important to the patient. Being able to accurately monitor the dose to high-risk organs (e.g., the eyes) when using implanted therapeutic radioactive seeds (brachyterapy) requires detectors with the best achievable spatial resolution.

In general, the health sciences are dominated (in number) by x-ray detectors, and improvements are constantly sought. Detection challenges are to maximize the range of detectable signals (i.e., rates), improve the spatial resolution to better than a few millimeters, better time resolution for coincidence measurements to reject background, improved efficiency, and to much lesser extent, energy resolution. Because of the widespread use of diagnostic X-rays, significant efforts are being expended to develop better inorganic scintillators (as described more fully in a later section). New ceramic scintillators with 10^3 pixels have enabled the continued evolution of the multi-head, spiral multi-slice computed tomography systems of today. Another example is fluoroscopy, in which 40 cm x 40 cm plates of amorphous silicon readouts of columnar CsI(Tl) scintillators are used for diagnostic purposes. Finally, a number of new approaches utilizing X-ray imaging are under investigation, in particular diffraction enhanced and phase contrast imaging, both of which involve coherent x-ray sources and detectors with high rate capabilities.

With an aging population and society's insatiable desire for improved diagnoses and treatments, the medical community will most assuredly drive the development of radiation detectors of all kinds for many years to come.

2.2 High Energy Physics

The second largest driver of detector technology is the high-energy physics community. Their large-scale experiments require detection of a wide range of charged particles at remarkably high intensities, energies, and interaction rates. These detectors often have to function in extreme radiation and magnetic fields. In recent years, silicon detectors have become the mainstay of these experiments, using either pixilated or strip detectors to track the motion of the incident and reaction products. As an example of the magnitude of these experiments, the CMS collaboration at Fermilab has proposed to use 450 m^2 of silicon detectors, with 10^7 strips, requiring 26 million wire bonds and 75,000 readout chips [2-3]. These are daunting engineering challenges.

Astrophysicists also contribute to the development of radiation detector technology, and in particular, radiation imaging methods. Unlike high energy physics in which the events typically occur at high energies over short time spans, astrophysicists look at the results from both low and high energy nuclear reactions for understanding cosmological phenomena, with time scales that range from microseconds (explosions) to mega-years (stellar evolution). While fast and thermal neutron detectors have been used to probe for low-Z materials in space objects, recent thrusts have involved more x- and gamma-ray imaging, (e.g., locating gamma ray bursts). These detectors must function over a range of difficult environments (-40 to 40 C), withstand severe launch forces, lack a reference ground, are susceptible to radiation damage (particularly from solar flares), and must satisfy severe weight and power limits [4]. Some of the cleverest imaging schemes have been introduced by astrophysicists, and involve modulating the source using either time- or spatially-varying masks between the source and detector [5-6].

2.3 Homeland Security

The newest application driver has emerged from the international concern over nuclear terrorism. In the United States, a new national agency with substantial resources has been forcing attention to the detection of clandestine nuclear materials, particularly at large ports of commerce. In this application, the major difficulty lies in distinguishing the relatively weak emissions of some interesting materials (in particular, U-235) among the background radioactivity encountered in everyday conditions. Industrial and medical sources, as well as naturally occurring radioactive materials (e.g., kitty litter, fertilizer) produce fields that can obscure those produced by significant quantities of the sensitive material. To underscore the difficulty of the problem, one estimate indicated that 90% of false alarms in passive detection systems come from people who have undergone a routine medical procedure.

Because the material being sought is so difficult to detect, every feasible combination of active and passive interrogation technology is being pursued, using every conceivable source, interaction mechanism, and daughter products. Deployed interrogation units commonly use either 6- or 9-MeV x-ray scanners to produce radiographic 2D density maps of the contents of containers, but ongoing research seeks to enhance these units by inducing and detecting fission from any fissile materials within [7-8]. In addition to large fixed systems, mobile vehicle-borne detection systems as well as portable detectors for first- and second-responders are being developed and deployed. Because these inspection systems will likely be deployed at many field sites, low cost and high reliability will be a key factor. With the threat of terrorism not likely to be eliminated any time soon, security agencies are expected to fund new generations interrogation sources and detector systems for the foreseeable future.

2.4 Other Applications

We should briefly mention, for completeness, other applications that influence detector technology. Industrial inspections that use x-rays (for inspection of parts), beta particles (thickness gauges), or neutrons (turbine blade inspections) all demand radiation detection technology. The energy industry, in particular fission power reactors, fusion experiments, and oil well logging, use nuclear techniques that place severe demands on radiation detection technology.The health physics community relies upon radiation detectors for dosimetry and continues to evolve new generations of TLDs, area monitors, and both real-time and integrating microsurvey meters. Finally, material science research, a field that exploits both neutron and x-ray diffraction, will benefit from advances in large area, position sensitive detectors. Often overlooked are the numerous other techniques that utilize ionizing radiation including electron microscopes, Rutherford backscattering, and Auger electron spectroscopy, all of which derive their signals from some form of radiation detector.

3. CURRENT DIRECTIONS IN RADIATION DETECTOR DEVELOPMENT

We shall presume that the reader has some basic background in radiation detection techniques, something akin to what can be found in G. F. Knoll's textbook Radiation Detection and Measurement. In what follows, we take a look at more recent developments in scintillators, gas filled, semiconductors, and miscellaneous detectors. For those who have glanced away since last studying this field, the remarkable advances in each of these areas over the past decade or so should be breathtaking.

3.1 Scintillator Detectors

Introduced in the 1940's, sodium iodide was essentially the first scintillator produced for radiation detection. Although the next six decades produced periods of intense research [cf. Fig. 1], amazingly, sodium iodide still remains the workhorse of the scintillators. The material is relatively inexpensive (common salt), is environmentally robust,

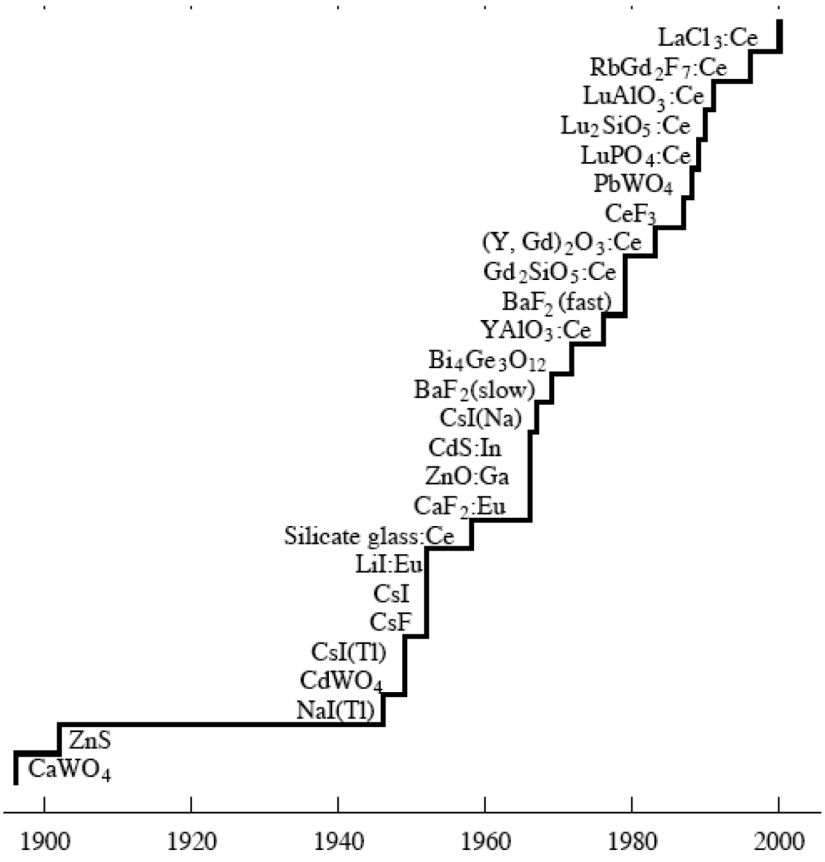

Fig. 1. The History of Scintillator Development, Taken from [11]

has favorable fabrication and material properties and can be grown in a cubic meter sizes. However, it is lacking in some desirable features, in particular the speed of its signal, its energy resolution and its effective atomic number. As a result, a number of new scintillators are emerging that improve in one or more of these categories [9-10].

Scintillators are typically classified as either organic or inorganic since the method by which they produce light is typically different. The organic materials typically have a low atomic number and therefore are not as useful for gamma ray detection applications (they are quite useful in fast neutron spectrometry). They are relatively inexpensive, and provide the fastest signals (~ sub-ns), and are favored when these features are at a premium. A recent example of this are the anti-neutrino detectors being tested for non -proliferation measurements near operating reactors. These may employ quite large volumes of liquid scintillators. Nevertheless, the majority of development effort has always been in inorganic scintillators having high atomic number, high scintillation efficiency, and a more linear output with energy, despite their undesirable property of generating their signals slowly (~10^2 ns).

Thus, while NaI(Tl) remains the world's most predominant scintillator, others, such as BGO, LSO, GSO, $CdWO_4$, and Cs(Tl) have found a place in x-ray and gamma-ray applications, along with today's ceramic scintillators used in CT cameras (favored for their insensitivity to "beam burn" of heat and radiation). And for neutron detection, the scintillator LiI(Eu) is frequently chosen because of its large neutron cross-section.

However, over the past few years, a number of interesting materials have emerged as scintillators that utilize Ce-like atoms as the primary scintillation source. These have included YAP(Yb^{3+}) (i.e., $YAlO_3$), YAG, and LuAP, all of which have light yields which are only about half that of NaI, but are significantly faster [9-10]. The biggest breakthrough appears to be the $LaCl_3$ and $LaBr_3$ scintillators, activated with Ce^{3+} [12]. These two materials not only provide much faster signals (~30 ns), but also much better energy resolution. Unlike many other materials that showed promise in small volumes, these hygroscopic materials are already produced in sizes large enough for practical applications. While standard inorganic scintillators could only provide energy resolutions of ~8% at 662 keV, these new materials routinely provide energy resolution of ~3% due to their enhanced light yields and linearity. Spectral lines that were previously indistinguishable using scintillators can now be seen clearly, which has opened new applications. While the costs are already well below those of equivalent-sized semiconductor detectors, these should continue to decrease while active volumes increase. Already, 3" x 3" $LaBr_3$(Ce) crystals are available at ~$150 US per cm^3 simply due to more capable furnaces.

While the Ce-activated scintillators have moved scintillators into a new realm of potential applications, the ~50,000 photons/MeV currently achieved does not equate to the fundamental limit imposed by the band gap. Better crystalline hosts for the Ce^{3+} activators that can improve resolution to 1-2% seem within reach. However, the fact that these scintillators use activator atoms introduces an avoidable energy inefficiency since some energy must be lost nonradiatively to the activator atoms in the band gap. Recently, Derenzo [11] has noted that room temperature semiconductors are capable of scintillation. In fact, the semiconductor-scintillator PbI_2 would yield another factor of 2 improvement in energy resolution if carrier trapping on nonradiative trapping centers could be alleviated.

To summarize, a number of applications require better energy resolution than scintillators had been capable of providing. As a result, the only viable option had been the use of expensive and complex semiconductors. Research in ceramic scintillators will remain quite active due to their radiation hardness. But with the new generation of Ce-activated materials, scintillators appear to be on the verge of filling that energy resolution gap.

3.2 Optical Light Readout Devices

The scintillator detector typically produces visible photons that must be converted to an electronic signal for processing, a task typically accomplished by a photomultiplier tube using a bialkali photocathode whose absorption spectrum matches the emission spectrum of common scintillators. These optical readouts are a critical part of the detector system, and have also undergone a rapid evolution in recent years. Compact photomultipliers that occupy a much smaller volume are now readily available, some of these with the ability to measure the light intensity in 2D on a millimeter scale over a 5-inch diameter face [13]. This ability to measure the centroid of the light distribution is critical in most imaging applications. Another common photocathode-based device is the multichannel plate, frequently used in mass spectroscopy, low light level imaging and all types of electron microscopes [14].

Silicon converters have emerged as a major alternative to PMTs for some applications. Because of their immunity to magnetic fields, small sizes, low-power requirements and high conversion efficiency, they offer an attractive light conversion option for scintillators whose emissions overlap silicon's higher wavelength absorption spectrum. Some success in introducing multiplication of the signal within the silicon has been achieved, but only over relatively small areas [15-16]. Without multiplication, the inherent electronic noise of silicon converters limits their utility to incident photons having more than a few hundred keV. One method to reduce this noise is to shape the electric field with external contacts that force the electrons to a small electron collection area. These are known as silicon drift photodiodes and are being actively spearheaded in detector laboratories [17]. As a compromise between a PMT and photodiode, the hybrid photodiode uses a photocathode, but accelerates the photoelectrons across a large potential (~10 kV) to create an enhanced signal in the silicon

photodiode [18]. These are commercially available, although the small sizes are limiting for some applications.

Other advancements include introducing position sensitivity with light conversion in silicon. The typical CCD provides this ability, but functions by integrating the signal over fixed periods of time rather than by recording each event as required for spectroscopic applications. Instead, pixilated CMOS devices have been designed that provide event-by-event readout (also known as active pixel sensors) [19]. The current generation devices include an embedded transistor with each pixel, thereby minimizing noise at the expense of some dead space introduced at the surface of the converter [20]. The latest variant of this design, the depleted field effect transistor, or DEPFET, uses the flow of signal carriers in each pixel to modulate the gain of an attached transistor [21]. Such devices have demonstrated very low noise (12 electrons) and very small pixel dimension (~50 microns), and should prove exceptionally useful in imaging applications as this technology matures.

Organic semiconductors on silicon substrates, used commonly in optical application such as phototransistors, LEDs, and lasers, are also being considered for possible light readout applications since they can completely cover a scintillator [22]. Their low atomic number and mobility generally restricts their use to a light converter rather than a direct radiation detector. Current technical challenges facing organic semiconductor development includes finding useful surface contacts by matching the work function of common metals.

The ability to pixilate on silicon has been extended to ever finer scales, ~20 micron sizes, and has finally led to the silicon PMT – an exciting new concept in light conversion [23]. The concept is similar to the pixilated avalanche photodiode, except that each pixel is operated in avalanche mode and therefore will count either zero or one photoelectron. Early designs have shown high signal gain (10^6), low voltage requirements (24V), and the potential for low noise (not yet realized). By simply counting the number of fired pixels, one has a digital measure of the signal, thereby obviating the need for further pulse processing. This gain in simplicity comes at a cost, namely the need to monitor many pixels ($\sim 10^3/mm^2$) simultaneously. Nevertheless, if large areas can be produced cost effectively, this may represent a breakthrough in light conversion technology.

3.3 Gas Filled Detectors

Gas-filled detectors are the ancestors of all modern radiation measuring instruments. Inexpensive, robust, and available in a variety of sizes and shapes (cylindrical, spherical, or planar geometries), they continue to play an important role in detection, particularly in routine survey meters. In high-energy physics, the multiwire proportional chamber (for which G. Charpak received the 1992 Nobel prize in physics) is still used to provide large-area energy and position sensing for important beam experiments [24]. These are available commercially in sizes approaching 1 m^2 with spatial resolution ~ $1mm^2$. Recently, the development of a series of gas filled detectors utilizing fine contacts on silicon has been evolving (microstrip gas detector, microgap chamber, multidot detector, etc.) [25-26]. They share the feature of the gas proportional detector: a high electric field around a small anode to induce localized gas multiplication, but are easily produced using silicon fabrication technology with much finer features than found in a wire-based gas chamber. Inhibiting their progress was the problem of buildup of the cation on the substrate, but this appears to have been resolved. One particularly popular recent design under active development is the gas-electron multiplier (GEM) in which foils containing small shaped holes (~70 micron diameter, ~100 holes/mm^2) provide the electric multiplication [27-28]. The degree of multiplication of the signal is relatively modest (~10), but can be increased by utilizing multiple layers of these foils, known as multi-GEMs. With the current shift to silicon-based detectors for high-energy physics applications, GEM detector research has slowed in recent years, but still remains active.

The other gas-filled detector concept that is receiving attention is the high-pressure xenon detector [29]. With sufficient pressure, the high Z (54) of xenon provides enough stopping power for it to be promising as a gamma ray spectrometer. At higher pressures, impurities tend to deteriorate the detector response by trapping carriers, and therefore must be avoided. Overcoming the purity problem has proven more challenging than expected and has recently led researchers to look at applying single carrier techniques (see the discussion on semiconductors below) to mitigate this.

3.4 Semiconductor Detectors

For the past half-century, detectors made from semiconductor materials have served as the gold standard for gamma and x-ray spectroscopy. Silicon and germanium are the primary materials of choice, despite their low values of the atomic number (14 and 32). Their primary advantage is that they are monatomic and therefore easy to obtain and grow. The resulting crystals have high purity and very few of the defects and traps that interfere with the flow of the signal carriers. Semiconductors, as a group, are advantageous for spectroscopy because the energy required for a single signal-carrier pair, namely an electron and a hole, is only a few electron volts. As a result, for a given energy deposition by the quantum of interest, more signal carriers can be produced. With more carriers, there is less relative statistical noise in the signal, and hence, better energy resolution is possible.

While a smaller amount of energy required to create a signal carrier (i.e., smaller band gap) should yield better energy resolution, it also increases the probability for competing thermally generated carriers. Limiting the active detector volume or using cryogenic cooling normally is

adopted to mitigate this problem. But these restrictions limit the utility of these devices to typically laboratory-type operations.

As a result, semiconductor detector research has moved in two directions: pixilating existing semiconductors to make them position sensitive, and employing compound semiconductor materials with higher atomic numbers and larger band gaps that will allow high energy-resolution spectroscopy for gamma rays at room temperature operation. We address both of these trends below.

The standard high-purity germanium gamma ray spectrometer has changed little except in size. From only golf-ball sized crystals, crystals are now grown in 10 cm diameter wafers, with the largest detectors having an efficiency that is twice that of the standard cylindrical 3-inch by 3-inch NaI scintillator [30]. By using thin end windows and n-type base material, germanium detectors can now be used for low energy x-rays, a field formerly dominated by silicon detectors. More interestingly, these larger volumes (either in planar or coaxial geometries) are being segmented or stripped (typically a few mm pitch, but finer dimensions are being pursued) to permit position sensing for imaging [31]. Amorphous germanium contacts, a rediscovered concept, have dramatically improved the yield and reliability of these position-sensitive devices. Finally, work on mechanical coolers, historically too noisy for practical applications, has enabled portable operation without requiring a supply of liquid nitrogen. A recent example is the ORTEC Detective, a portable HPGe detector with only a small loss in energy resolution from the mechanical cooler.

While germanium and silicon detectors have undergone steady evolution, the excitement in semiconductor detectors is the breakthrough development of the II-VI compound semiconductors, in particular, Cadmium Zinc Telluride and Mercuric Iodide [32]. Material problems still plague the production of large volume crystals (> few cm^3) without excessive defects and traps. Fortuitously, these defects primarily affect only the motion of the holes. A number of techniques to avoid trapping losses and the slow hole movement have been attempted, but resulted in an unacceptable loss of efficiency or complex pulse processing. But by employing techniques that are sensitive only to the motion of electrons [33], these materials are now capable of producing reasonably good energy resolution at room temperature. While there has been a gradual increase in the volumes of these detectors, they're still physically small relative to their competition, but compensate somewhat with significantly higher stopping power.

The idea behind this clever approach requires a basic understanding of signal generation within a detector. The Schockley-Ramo theorem predicts that most of the signal induced on a small electrode occurs only when the carriers are in the immediate vicinity of the electrode. Thus, the difference in the signals from a collecting and noncollecting anode becomes large only near the point of collection. Since the desired signal is the number of carriers, regardless of the position of interaction or the path to collection, this subtraction technique works well. Using this approach, compound semiconductor detectors with an energy resolution of approximately <1% (at 662 keV) have been reported in a laboratory setting (~3% is routine), and future gains are possible with improvements in low noise multipixel readout electronics, better materials, and a more thorough unde-rstanding of the role of growth parameters and surface contacts. This energy resolution is already sufficient to enable field applications, including space physics, homeland security, IAEA inspections (using a point anode and 5-sided cathode), and medical probes. Although still dependent upon government funding to subsidize progress, these successes have been enticing to commercial entities needed for the long- term viability of this technology.

3.5 Ultrahigh Energy Resolution Detectors

There are a few applications or situations in which the ultimate in energy resolution is advantageous [cf. Fig. 2]. One must typically sacrifice absolute efficiency and portability, but the results can be remarkable. In this section we take a look at these novels detectors in which the energy resolution is so good that one can distinguish chemical states from the x-ray lines [34].

To achieve electron-volt accuracy, one must produce more signal carriers than possible using ionization techniques. Instead, one can exploit the fact that superconductors have pairs of electrons (Cooper pairs) that are bound very loosely (~meV), and then diffuse any electrons that become unbound as a result of a radiation interaction across a barrier. These superconducting tunnel junction detectors [35] can be found at synchrotron radiation facilities, and have energy resolutions of a few electron volts at several keV.

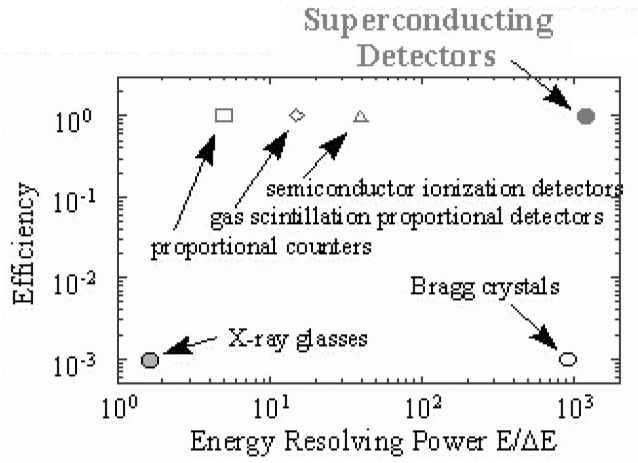

Fig. 2. Intrinsic Efficiency Versus the Inverse of Energy Resolution. Taken from [36]

Another approach that has achieved even better energy resolution is to use the detector as a calorimeter. Here, the carriers are the phonons in the device, and the energy per carrier is only micro-eV. The absorption of a quantum increases the temperature of a Sn crystal, and a sensitive Mo-Cu thermometer measures the temperature rise. Since $T=(Q/mC_p)$ and $C_p \sim T^3$, the detector's mass must be very small and operated near absolute zero in order to register a measurable temperature rise from the radiation interaction. These micro-calorimeters are used in astrophysics and have achieved an energy resolution of .005% at a few keV. For comparison, the best semiconductor detector would achieve 2% at this energy.

Finally, for completeness, a third category of low-temperature detector is the superconducting grain detector. These detectors are operated at their transition temperature for superconductivity. Upon radiation absorption, the slight increase in temperature switches the grain to a nonconducting state. With an external magnetic field applied, the shift is accompanied by the penetration of the magnetic field into the grains (i.e., the Meisner effect). This changing magnetic field is sensed externally, as is the switch back to superconductivity as it is cools off. The time difference between these transitions is proportional to the energy deposition, which is the signal of interest.

4. SUMMARY

Radiation detection is a broad and vital field that services a wide-ranging set of applications. The field capitalizes on advances in basic and applied physics, engineering, and mathematics to develop more capable measurement systems. In recent years, new capabilities have been enabled by introducing position sensitivity in detectors as well as miniaturized multichannel data acquisition systems. Advances in silicon fabrication techniques will continue to be exploited for radiation detectors and their associated electronics. Low noise, low cost, room temperature electronics with multiple channels are currently a limiting factor. Similarly, room temperature semiconductor and ultra high-resolution superconducting spectrometers have demonstrated remarkable capabilities recently and are expected to play an increasingly important role in the future. With heightened concern over nuclear security added to the constantly expanding need for radiation measurements, we can expect an accelerating pace of development in this field.

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