Adaptation of Radiation Detectors for Sustainable Development

Purba Bhattacharya[*a], Supratik Mukhopadhyay[b], Nayana Majumdar[b]

ABSTRACT

A variety of sophisticated radiation detectors is used in laboratory and field-based experiments related to particle physics, nuclear physics and related branches of science and technology. Many of these experiments are curiosity driven, while some of them have social applications. In this letter, we will discuss some of the prominent gaseous ionization detectors and their possible adaptation towards a sustainable future. Recent experimental and numerical research in the use of environment friendly gas mixtures to be used in such detectors will be covered in some detail. In addition, their application in sustainable and socially relevant technologies will be briefly mentioned.

I. Introduction

Transmission of energy in the form of waves or particles is broadly considered to be radiation. It is a generic term that encompasses gravitational, acoustic and electromagnetic waves, massless neutral particles such as X-rays and γ-rays, neutral or charged massive particles, such as neutrons, nuclei, nuclei fragments, electrons, protons, other elementary particles such as neutrinos [**1**]. The passage of radiation may occur through a material medium, or through empty space. Depending on the energy of the particles, a radiation can be ionizing and non-ionizing. In this paper, we will consider only the ionizing radiations. The source of this kind of radiation can be natural, such as the cosmic microwave background, stellar / galactic radiation, natural radioactivity from terrestrial environment. It can also arise out of anthropogenic sources such as mining activities, refinement and preparation of radioactive isotopes, process of nuclear power generation, nuclear explosion etc.

Detection of radiation is of utmost importance for activities related to the exploration the universe, as well as to categorise constituents of objects in our immediate vicinity. Using radiation detectors, it is possible to explore fundamental constituents of matter and events of astrophysical importance, to evaluate the safety of a nuclear power reactor or a particular living environment, as well as to produce images of various objects of interest for further processing that can have huge impact on topics such as cancer treatment.

Impact of ionizing radiation detectors on science, technology, and society in general, has led to intense activity in the field since late 19th century. At present, there is a wide variety of ionization detectors available, some of the more prominent ones are gaseous detectors, semiconductor detectors, solid-state detectors, scintillators and Cherenkov detectors. Passive detectors such as photography emulsion, radiographic films, nuclear emulsion detectors also are used in appropriate fields [**2**].

Gaseous ionization detectors are among the oldest radiation detectors. They work on the ionizing effect of incoming radiation as a result of its interaction with the gaseous medium. The resulting electrons and ions are made to drift towards different electrodes by the application of suitable electric field. In addition, the fast drfiting electrons participate in further ionizing the gas molecules, giving rise to various ionic states. The

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a Department of Physics, School of Basic and Applied Sciences, Adamas University, Barrackpore-Barasat Rd, 24 Parganas North, Jagannathpur, Kolkata, West Bengal 700126
b Applied Nuclear Physics Division, Saha Institute of Nuclear Physics, 1/AF, Sector I, Bidhannagar, Kolkata, West Bengal 700064
**Corresponding author email id:*
purba1.bhattacharya@adamasuniversity.ac.in

movement of these charged particles induces signal on readout electrodes which are collected and processed to understand the nature of the incoming radiation itself [**3**]. This is shown by the simple illustration in Figure 1.

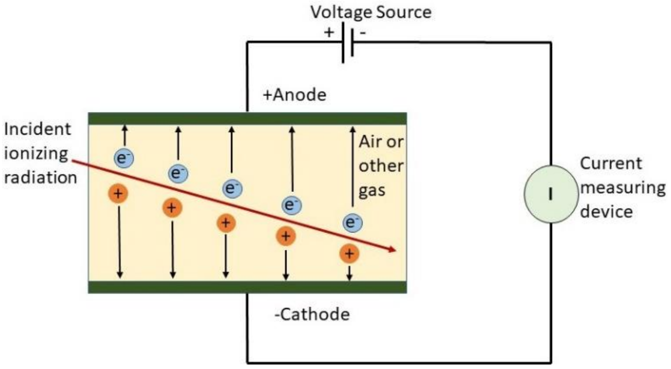

Figure 1: Schematic presentation of the working of a gaseous ionization detector.

Due to their excellent position, timing and energy resolutions, very good rate handling capability, favourable ageing characteristics and ability to cover large geoemtries at reasonable expenses, gaseous detectors are favoured in a large number of fundamental physics experiments, as well as, societal applications. For example, significant fraction of detectors in different on-going LHC experiments and their proposed upgrades are gaseous detectors [**4, 5, 6**]. Many proposed experiments also intend to use such detectors [**7, 8**]. Gaseous detectors also find their applications in nuclear physics experiments [**9**] and in tokamak plasma physics [**10**]. They are also extensively used various applications such as dosimetry [**11**], fire detection system [**12**] medical imaging [**13**] and muon tomography [**14**].

Gas-filled detectors find applications also because optimized gas mixtures have already been identified for charged particles (nuclear and particle physics), X-rays (astronomy, synchrotron physics) and neutrons (neutron scattering that can have implications in airport and border security) [**15**]. Although ion transport is a subject that still needs lot of improvement, electron transport characteristics in various gaseous media are reasonably well characterized, are found to be favourable and allows good amount of gain to enhance signal over many orders of magnitude [**16**]. As shown in Figure 2, a single electron can create an avalanche of electrons if assisted by a large electric field in the amplification gap. By the use of suitable gas mixture, signal can be obtained arising out of fluorescence emission, as well. Finally, the mass of the gaseous detectors are usually quite low, and can be made even lower by working in less than atmospheric pressure, if needed. This can lead to reduced multiple scattering, beneficial for many experiments. Due to the very wide variety of applications involving gaseous detectors, it is important to ensure that they are safe for the environment.

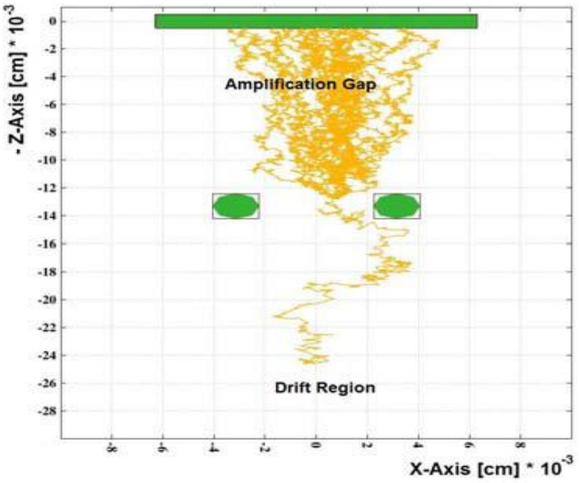

Figure 2: Single electron avalanche in a Micromegas detector

Besides making attempts to make the gaseous detectors and their subsystems friendly to the environment, there is a huge possibility of using them for taking care of the environment and develop other sustainable technologies based on such detectors. For example, the Geiger-Mueller counter (GM counter) is an instrument that is being used for almost a century to monitor radiation level in a given environment [**2**]. Similarly, radiation dose measurement using dosimeters has been an area of immense importance in which gaseous detectors have long been used [**11**]. While good amount of development is being carried out in both the mentioned areas, few recent application of gaseous detectors have attracted significant attention during recent years, namely, cosmic ray muon imaging [17] and development of flame, smoke and spark detectors, the latter especially in relation to repeated disasters due to wildfires / bushfires across the globe [**12**].

In the following sections, we will cover only two of the large variety of topics indicated above. They are 1) attempts to find ways of reducing release of greenhouse gases to the environment during use of different gaseous detectors, and 2) cosmic ray muon imaging as an example of sustainable application of gaseous detectors.

II. Literature Review

Gaseous detector utilize a gas, or a mixture of gases to produce different interactions between the incident particle with the medium. Unfortunately, some of the gas mixtures, although extremely suitable from the experimental point of view, are not environment friendly. Gases such as chlorofluorocarbons (freons), sulphur hexafluoride (SF6) have played important roles in tradiational gaseous detectors. For example, freons have been regularly used in popular detectors such as the Resistive Plate Chambers (RPC) [**18**]. SF6 has been used in high-voltage supplies, as well as in RPCs where it plays the role of an extremely effective quencher [**18**]. Unfortunately, the Global Warming Potential (GWP) of Freon and SF_6 are 1300 and 23500, respectively [**19**]. Similarly, isobutane has been used in various detectors such as the MICRO MEsh GAseous Structures (Micromegas) [**20**]. As an example, in Figure 3 we show the measured and simulated gain variation for Micromegas detectors using argon-isobutane gas mixture. Two detectors of the same specification were used for the measurements. The importance of including the Penning effect in computations is clearly demonstrated in this figure. The isobutane gas has even been used in the purest form in few experiments despite its high flammability. Thus, many of these gases needs to be phased out without further delay. In any case, due to ban in different countries, they will be very hard to procure and their prices are expected be volatile in the coming years.

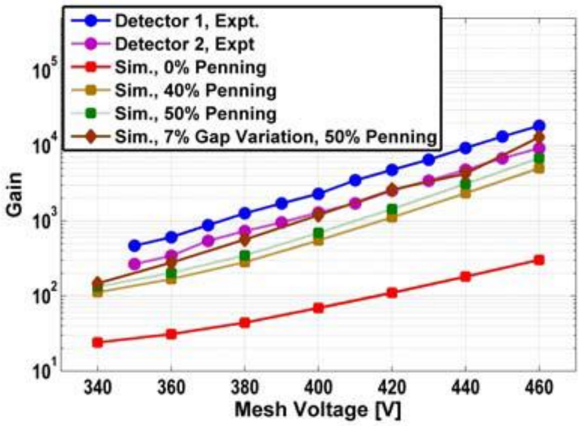

Figure 3: Comparison of experimental gain with simulation in argon-isobutane (90:10) gas mixture for two bulk Micromegas detectors having amplification gap of 128 μm and pitch of 63 μm.

Several new gases are being actively considered to replace them, experiments and numerical simulations being conducted towards this goal. Among the potential candidates, tetrafluoropropene (trade name of hydro-fluoro-olefine HFO-1234ze) is among the most promising ones [**21, 22**]. Several numerical studies have been conducted for RPCs [**23**] that has resulted into different options of eco-friendly gas mixtures. Some of these studies have adopted the fluid approach to model transport of charged particles through a background gaseous medium [**24**], as described below:

$$\frac{\partial c_i}{\partial t} + \vec{\nabla}\cdot\left(-D_i\vec{\nabla}c_i + \vec{u}_i c_i\right) = R_i$$

$$R_i = S_e + S_{ph}$$

$$S_e = \left(\alpha(\vec{E}) - \eta(\vec{E})\right)|\vec{u}_e| n_e$$

$$S_{ph} = \xi Q E_{gas} \mu \psi_0$$

The above set of equations represent the drift-diffusion-reaction mechanism as the transport of dilute species (electrons, ions) through a solvent medium (neutral gas). For the i-th species, c_i, D_i, u_i, and R_i are the concentration, diffusion coefficients, velocity and rate of production, respectively. The rate of production depends on the source terms S_e and S_{ph} which represent Townsend multiplication and photo-ionization. Considering electrons, it is observed that S_e depend on the Townsend (⍰) and attachment (⍰) coefficients for electrons, in which n_e is the concentration. Similarly, source term related to photo-ionization depends on photo absorption coefficient (⍰) and the UV photon flux (⍰$_0$), where fraction of excited states that can ionize the gas is indicated by ⍰ and quantum efficiency to produce electrons due to photon absorption by the gas mixture is QE_{gas}.

In addition to the gases used within the detector, gas mixtures or liquids used to cool the detector system and those used in electronics and other subsystems, can also be harmful to the environment. Additionally, there is the problem of flammability and toxicity related to some of these gases. While it is true the performance of a gas mixture is of utmost importance for the physicist / technologist, it has now become imperative for all involved to be careful about the carbon footprint we leave behind due to our various activities and a proper balance has to be achieved. As a result, serious efforts are being invested by the gaseous detector community to find suitable replacement of all kinds of materials that are harmful to the nature [**25**]. In addition to searching eco-gases, new design considerations related to the reduction of energy consumption, increased overall energy efficiency are being formulated by different experimental groups.

It is expected that the concern felt by the scientifitc community in general, and gaseous detector experts in particular, will have great beneficial effects across the society. [**26**].

Gas recirculation through appropriate filter sysems is the most opted for technnology adopted in most of the large scale experiments in order to reduce the release of gases to the environment and to reduce expenses [**27**]. This requires fabrication of properly sealed detectors. However, there is a finite threat related to possible leaks that needs to be very carefully incorporated in the overall design of any experiment / application [**28**]. Unfortunately, recirculation is beset with difficulties due to its association with enhanced detector aging that needs careful investigation to ensure that experiments / applications do not suffer. [**29**]. Pollutants, if not properly filtered out can also lead to unreliable detector response and defeat the very purpose of setting up the experiment. Both these areas are being very actively investigated by the gaseous detector community [**26**].

Cosmic ray muon imaging has turned out to be a relatively new area of interest, although it was initiated during mid 20th century in Australia [**30**]. The method received some attention when Alvarez et al [**31**] tried to probe the interior of Chephren pyramids in Egypt. However, the real impetus came at the turn of the century when several groups made succesful attempts to monitor volcano activities in Asia [**32**] and Europe [**33**]. Soon the potential of muon absorption and scattering tomography was realized by a large number of scientists world-wide and the number of applications increased very fast to include fields as diverse as geophysics, mineralogy, security and volcanology [**34**]. The scattering of muons due to their passage through a medium depends on the atomic number and the density of the medium, as shown below:

$$\sigma = \frac{13.6\,MeV}{\beta c p}\sqrt{\frac{L}{X_0}}\left(1 + 0.038 ln\frac{L}{X_0}\right)$$

$$X_0 = \frac{716.4(g/cm^2)}{\rho}\frac{A}{Z(Z+1)ln(287/\sqrt{Z})}$$

We have considered σ as the width of a Gaussian distribution of multiple coulomb scattering angles projected onto a plane for muons with momentum p. Here, *c* is the speed of light and *β* = *v/c* is the ratio of the speed of muon, *v*, to that of light. *L/X*0 is the scattering medium thickness in terms of its radiation length, *X*0. *X*0, in turn, is related to atomic weight, *A*, atomic number, *Z*, and density, *ρ*. The equations suggest that the magnitude of muon scattering significantly depends on *Z* and *ρ*. Therefore, muons undergo larger deviations while traversing through high-Z and dense matter such as lead, uranium. On the other hand, lighter materials, like concrete, aluminium, can cause only feeble scattering. Thus, it is possible to identify the atomic number and density of a hidden object if enough number of muon pass through it and their scattering information is collected and processed. Several groups used this approach to produce a generic Non-Destructive Evaluation (NDE) technique that was used to probe and monitor large structure of archaeological and civil interests [**35, 36**]. This approach is qualitatively illustrated in figure 4.

One such very interesting application was the imaging of the Khufu pyramid that seemed to indicate that there is a hitherto unknown large void within the great pyramid [**37**].

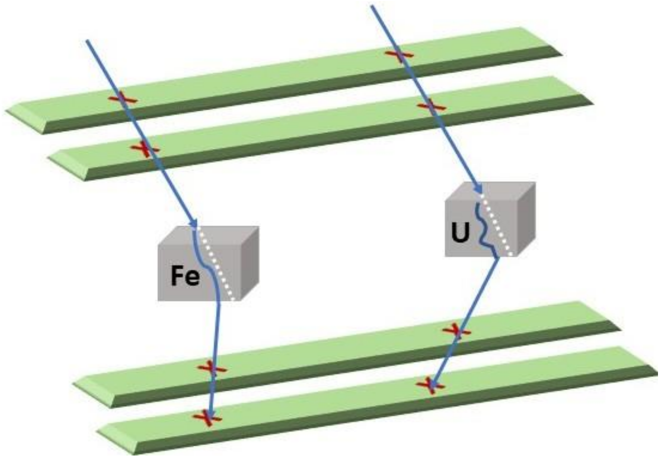

Figure 4: Incoming muon is scattered more by uranium than iron. Note that the angles are exaggerated.

Different σ-s of the MCS of muons passing through different materials can be estimated using the above equation, as shown in Table 1. For the purpose of the present estimates, it has been assumed that muons of 1GeV are traversing a length of 10cm through a given material. The same information has been plotted in Figure 5 which clearly shows that both Z and density has strong influence on the value of σ.

This information is used by muon imaging applications to discriminate between different materials.

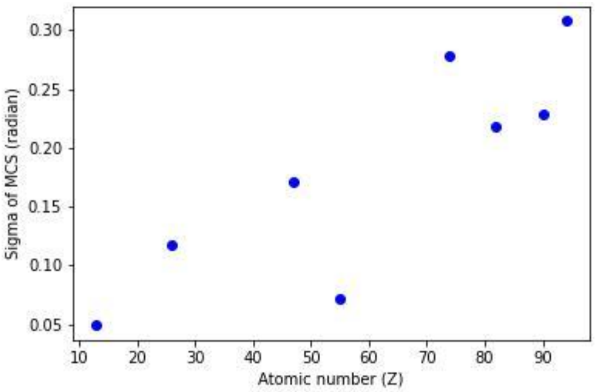

Figure 5: Variation of sigma of MCS with Atomic number

Appropriate utilization of tomographic algorithms and other image processing techniques can provide information about the internal structure of the object materials in the path of the atmospheric muons.

Table1: Numerical value of σ for different material

Material	Atomic number (Z)	Density (gm/cm^3)	σ of MCS (rad)
Aluminium	13	2.7	0.049
Iron	26	7.874	0.117
Silver	47	10.49	0.171
Caesium	55	1.879	0.072
Tungsten	74	19.25	0.279
Lead	82	11.34	0.218
Thorium	90	11.724	0.229
Plutonium	94	19.816	0.307

III. Future Prospects

entification of eco-friendly gases that can satisfy the science requirements of an experiment, or application, is of utmost importance. Detectors design modifications may also need to be carried out so that use of such green gases does not undermine the experimental goals. The field suffers from the lack of experimental data, as well as numerical simulation, on candidate gases. Electron and ion scattering cross-sections and transport coefficients need to be measured and simulated. An excellent database is maintained at LXCat which is oriented towards non-equilibrium low temperature plasmas [**38**] that needs to be augmented extensively. Novel ways of recirculation and purification of gas mixtures can also lead to eco-friendly gaseous detectors. Muon imaging can help in a very big way to a sustainable future. Some of the areas in which it has already shown clear signatures of success are 1) NDE of civil and other large structures, 2) identification of radiation sources, especially the undesirable clandestine ones, 3) monitoring nuclear waste, including malfunctioning nuclear reactors, 4) monitoring carbon-dioxide sequestration, 5) monitoring volcanoes etc. Improvements in detector designs leading to better position, energy and time resolutions will surely lead to even more diverse applications and improve performance in the existing ones. In addition, there is huge possibility of improvement in actual tracking of the atmospheric muons and extracting information out of the scattering vertices leading to 2D, or tomographic 3D, images of the object interior. There is big scope of application of novel algorithms such as machine learning in this exciting field.

IV. Conclusion

In this paper, we have discussed the urgency of developing environment friendly gaseous ionization detectors. Different approaches that are being adopted to ensure this imporvement have been mentioned. Importance of identifying eco-friendly gases suitable for gaseous detectors and its subsystems has been briefly put forward. Other possibilities of enhancing environment friendliness have been indicated.

Employment of gaseous detectors in the development of various sustainable applications has been briefly explored. Several areas have been identified in which such detectors can play a leading role. Cosmic ray imaging using gaseous detectors has been introduced. It is clear from these different aspects that gaseous ionization detectors can be used in a big way to develop succesful applications that are green, sustainable and less resource hungry.

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