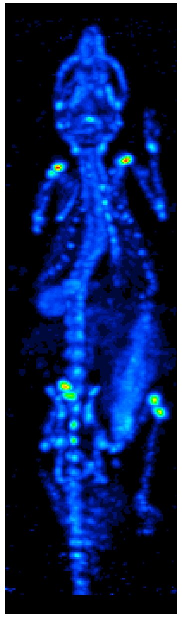
Gamma Ray Imaging and its Applications

ADITYA GARG

Introduction

Gamma Ray Imaging is a relatively new field with applications in diverse fields. As the name suggests, the basic principle involved is recording information about radiation coming from some radionuclide(s). The method has been put to use to image tumors and cancerous tissues in a human body. It is also used for locating minerals with radionuclides through surveying and Astrophysics uses gamma ray imaging to collect data about pulsars through telescopes.



Three Broad Applications Of Gamma Ray Imaging:

Medicine Physics

Gamma Ray Astronomy

Spatial Localization of Radioactive Sources

Gamma Ray Imaging in Medicine Physics:

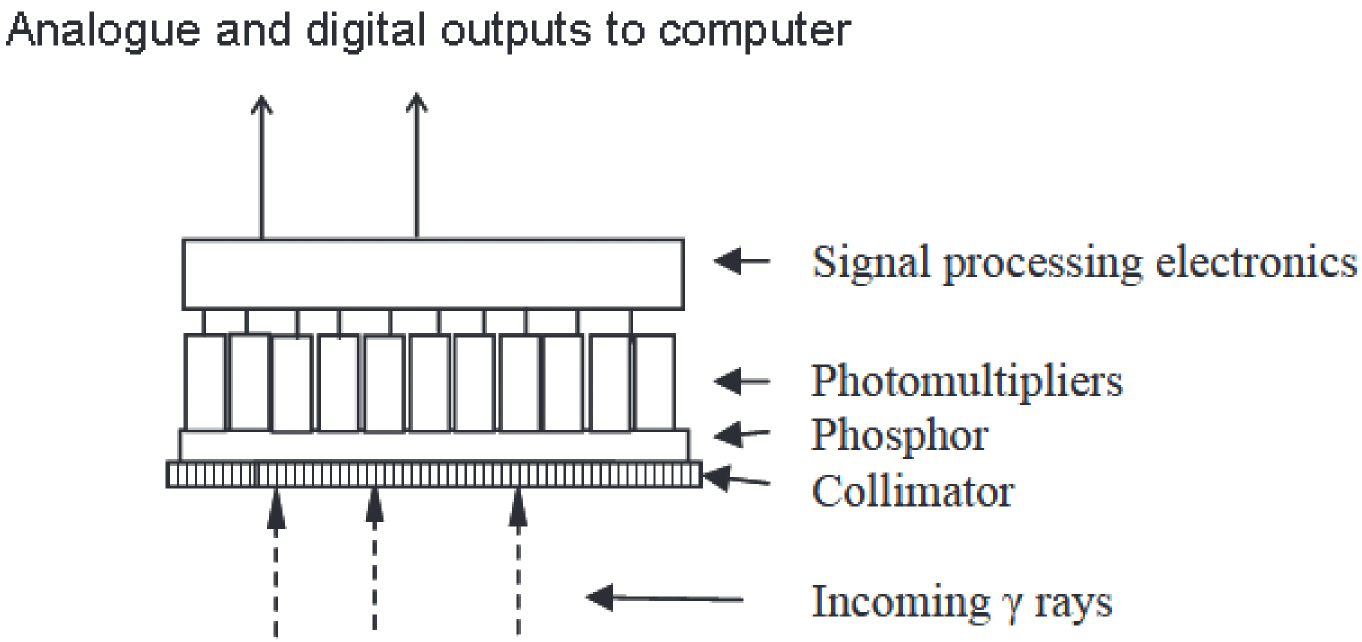
In Medicine Physics, Gamma ray imaging revolves around injecting the patient with a suitable non-harmful isotope of some radio nuclide coupled with some molecule and then record the gamma rays emerging from the body. The coupling molecule is chosen so that it is selectively absorbed in those locations of body which we need to image. For example, If we want to know the location of a tumor in a patient we select the coupling molecule such that it is concentrated at the tumor in the body.

Radio Nuclides

^{99m}Tc	**^{99m}Tc-Bisphosphonates accumulate at sites of bone mineral rearrangement**
	^{99m}Tc-Labeled colloids are used for lymphoscintigraphy and imaging liver and spleen
	^{99m}Tc-Hexakis-methoxy-isobutyl-isonitrile and ^{99m}Tc-tetrofosmin (a lipophilic cationic diphosphine) are used for myocardial perfusion imaging, identification of parathyroid adenoma, and identification of some tumors
^{123}I or ^{131}I	Iodide—localization of thyroid tissue
	Metaiodobenzylguanidine (MIBG), a catecholamine analog, localizing in pheochromocytoma and neuroblastoma
^{201}Tl	Ionic thallium used for tumor perfusion imaging
^{111}In-Pentetreotide	Detects overexpression of somatostatin receptors, especially in neuroendocrine tumors and lesions arising from the neural crest, such as carcinoid, paragangliomas, and medullary thyroid carcinomas
^{111}In-Capromab pendetide	Capromab pendetide is a murine monoclonal antibody which recognizes a transmembrane glycoprotein expressed by poorly differentiated and metastatic prostate adenocarcinomas
^{67}Ga-Citrate	Gallium forms a complex with transferrin or lactoferrin. Receptors for this complex are overexpressed on membranes of tumor and inflammatory cells

Source: Orsini, F., Lorenzoni, A., Erba, P.A., Mariani, G. (2013). Radiopharmaceuticals for Single-Photon Emission Imaging and for Therapy. In: Strauss, H., Mariani, G., Volterrani, D., Larson, S. (eds) Nuclear Oncology. Springer, New York, NY. https://doi.org/10.1007/978-0-387-48894-3_2

Basic Diagram of a Gamma Camera



Working Principle

The gamma camera (invented by H.O. Anger) comprises of a large area scintillator crystal made of NaI(Tl). A parallel collimator is placed facing it. Only those gamma rays incident perpendicularly on the plane of the crystal are able to pass through the collimator, rays at other incident angles get absorbed the collimator. When the gamma ray photons are absorbed by NaI(Tl), the scintillator crystal creates a burst of blue photons(~320 to 410 nm). The PMTs produce a signal that is proportional to the light generated in the crystal. Positional information can be obtained by comparing the size of the signals from different PMTs, whereas the energy information is related to the sum of the PMT signals.

Compton Imaging System

Compton imaging is an imaging technique that uses Compton scattering to produce images from a gamma-ray source. Compton imaging systems are also known as Compton cameras. The advantages of Compton imaging over other conventional imaging techniques are that it covers a wide range of energies. This system also makes it possible to construct a 3D image of a fixed object without moving the detector. Compton imaging well eliminates background radiation during scattering processes through energy separation.

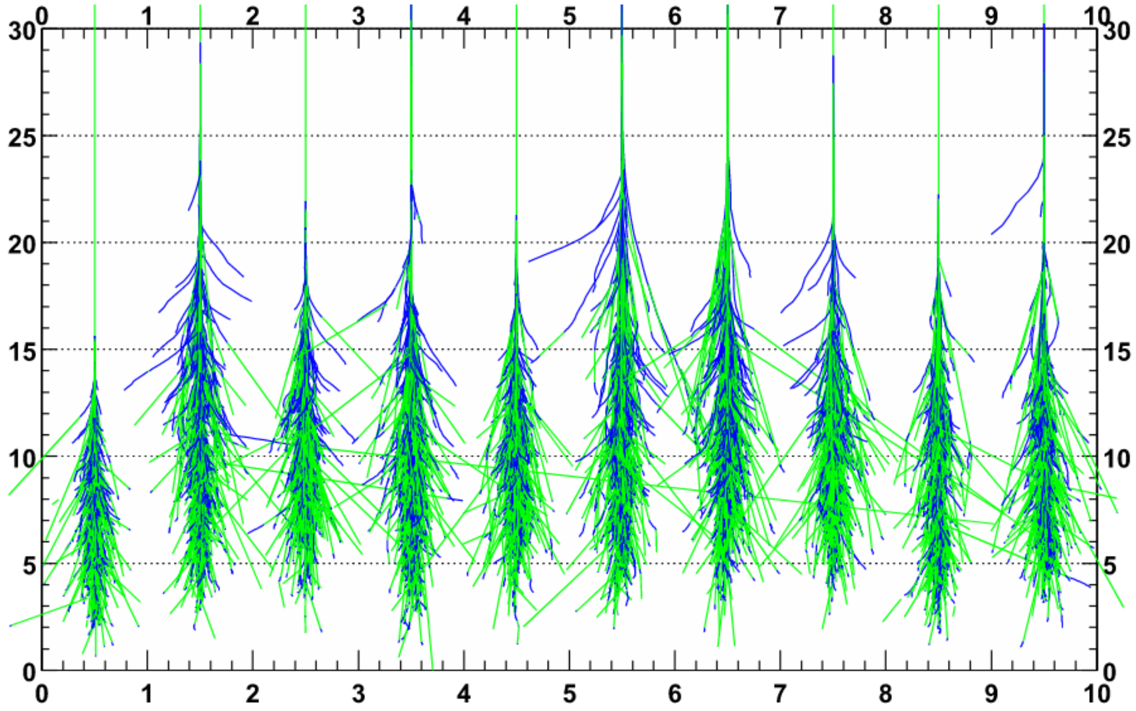
Gamma Ray Imaging in Astronomy

When a high-energy particle (γ ray or charged nucleus) enters the atmosphere, it can interact with the atmospheric nuclei through various processes, leading to the development of a so-called “extended air shower (EAS)” of particles. Electromagnetic showers, initiated by high energy photons or electrons, are governed by mainly two elementary processes:

– production of pairs of e± by the conversion of high energy photons in the Coulomb field of the nuclei;

– Bremsstrahlung emission of e± in the same Coulomb field, leading the production of further high-energy photons.

The energy of the impinging particle is then redistributed over many particles as the shower develops in the atmosphere.



Simulation of 10 showers, each initiated by a γ ray of 300 GeV.

Cherenkov Radiation

As an extensive air shower traverses the earth's atmosphere the relativistic charged particles in the shower emit Cherenkov light. Cherenkov light is the electromagnetic equivalent of a sonic boom. It occurs when a charged particle travels through a medium faster than light can travel through that medium. This speed is determined by the index of refraction of the medium. Cherenkov light is emitted primarily into the ultraviolet spectrum in a small cone around the direction of motion of the particle. A typical charged particle in an air shower will produce 10 to 20 Cherenkov photons per meter as it moves through the air. Since there are roughly 10^8 to 10^9 charged particles in an air shower near its maximum extent, these showers produce large amounts of ultraviolet Cherenkov radiation in the forward direction.

Detection of Gamma Rays in Astronomy

VHE gamma-ray astronomy rests on two basic detector technologies:

– Detectors that measure particles of the shower tail reaching the ground. This method provides a snapshot of the shower at the moment it reaches the ground and constitutes the so-called "particle sampler" technique.

– Cherenkov detectors for observing showers that died before reaching the ground, through the detection of the Cherenkov light produced in the atmosphere. This method uses the atmosphere as a calorimeter,

Detectors measuring shower tails

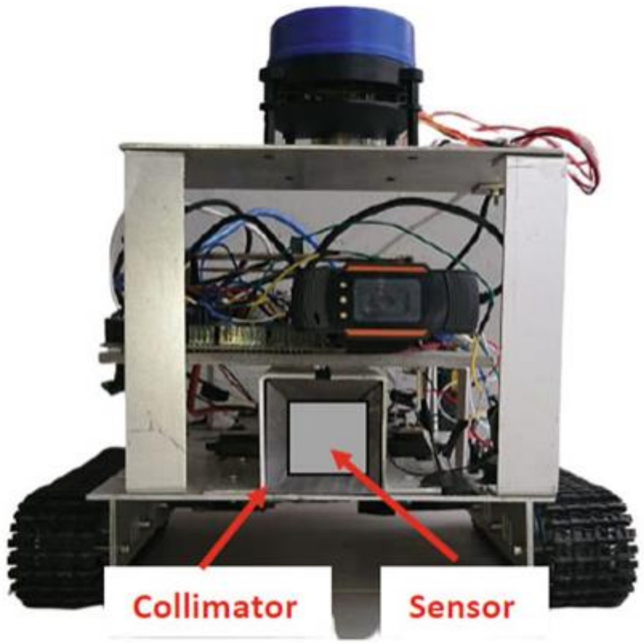
Detectors that measure particles of the shower tail reaching the ground. This method provides a snapshot of the shower at the moment it reaches the ground and constitutes the so-called “particle sampler” technique. Those detectors have a very large duty cycle (potentially 100%), but rather high energy threshold (as high energy showers are more penetrat-ing and produce charged particles at lower altitude than lower energy showers). Moreover, as they only have access to shower tails, they usually have a rather poor capability to discriminate the showers induced by γ rays from the much more numerous showers induced by protons and charged nuclei. Such detectors are usually installed at high altitude to collect more charged particles.

Cherenkov Detectors

Cherenkov detectors observe showers that die before reaching the ground, through the detection of the Cherenkov light produced in the atmosphere. This method uses the atmosphere as a calorimeter. Several techniques have been tried in the past. The most successful has been to use optical telescopes to take a "picture" of the showers (recording the Cherenkov light emitted by them). These so-called "imaging atmospheric Cherenkov telescopes" (IACTs) are characterized by a relatively small field of view (a few degrees of angular diameter), low duty cycle ($\sim$ 10%, corresponding to moonless, clear nights), but a very large effective area, corresponding to the size of the light-pool illuminated by the showers ($\sim 10^5$ m^2), and very powerful discrimination capabilities.

Radioactive Source Localization using GRI[*]

The localization of a radioactive source is done using a single sensor and a collimator. The basic idea is to increase the localization accuracy of such a device by moving the sensor inside a mechanical collimator. The device on the right is hosted in a semi-autonomous rover. The mechanical collimator is made of lead with at least 1 cm thickness. The sensor can move inside the collimator with a piston like mechanism. Laboratory experiments showed that source localization accuracy better than 20◦ can be achieved when the sensor head was 4 cm deep inside the collimator. Thus, the greater the depth of the sensor inside the collimator the better the localization accuracy is.



*J. Du, K. (K.) Iniewski (eds.), Gamma Ray Imaging, https://doi.org/10.1007/978-3-031-30666-2_5

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[1] Orsini, F., Lorenzoni, A., Erba, P.A., Mariani, G. (2013). Radiopharmaceuticals for Single-Photon Emission Imaging and for Therapy. In: Strauss, H., Mariani, G., Volterrani, D., Larson, S. (eds) Nuclear Oncology. Springer, New York, NY. https://doi.org/10.1007/978-0-387-48894-3_2

[2] Mary Lowe, Alex Spiro, Peter Kutt; Gamma camera imaging in an undergraduate physics course. *Am. J. Phys.* 1 January 2022; 90 (1): 51–58. https://doi.org/10.1119/10.0006168