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Single detector-dual scintillator anti-Compton probes

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Anti-Compton spectrometers have many applications in the fields of safeguards, medicine and security. One of the most important applications is in the location of low energy gamma sources in the presence of high-energy gamma background or the location of high-energy gamma radiation sources hidden within the same spread of radiation background. In most situations space constraints limit the application of large size detectors or classical anti-Compton spectrometers. We have designed a compact anti-Compton spectrometer based on a single chip, dual silicon photodetector optically coupled to isolated, annular scintillators. Preliminary room temperature testing with CsI(Tl) and LYSO scintillators demonstrate the readout capabilities of the spectrometer concept. We have measured an outstanding energy resolution of 12 % and 8 % for the 511 keV line from a ^{22}Na source used to excite a LYSO and CsI(Tl) respectively. The other variants of Si-CsI(Tl) probes is also discussed.

Антикомптоновская спектроскопия имеет множество применений в ядерной медицине, системах контроля и досмотра. Одной из наиболее важных черт этого метода является возможность определения низкоэнергетичных гамма квантов на фоне высокоэнергетичного фона или выделение источников высокоэнергетичных частиц из широкого радиационного фона. Во многих случаях классические антикомптоновские спектрометры имеют ограниченное применение из-за размеров детектирующей системы. В рамках настоящего исследования разработан спектрометр на основе двойного кремниевого фотодиода сложной формы, состыкованного с двумя призменными сцинтилляционными кристаллами. Исследования при комнатной температуре показали работоспособность детектирующей системы для случаев использования сцинтилляторов CsI(Tl) и LYSO. Полученные значения энергетического разрешения составляют 12% и 8% (511 кэВ, источник - ^{22}Na) для LYSO и CsI(Tl), соответственно. Обсуждаются различные варианты Si-CsI(Tl) пробников.

Today the demands for nuclear spectroscopy instrumentation have increased. Such demands include good energy resolution for gamma and X-ray spectroscopy combined with the ability to work over a wide energy range of gamma photons for specialized instruments, which are searching specific isotopes with a particular signature in a combination with other isotope. Outstanding energy resolution is not always an issue however spatial resolution is becoming an important requirement for many fields of application. The main fields of application of such gamma spectroscopy instrumentation are safeguards, security and medicine.

This paper will provide short overview of problems where improved, portable gamma/X-ray spectroscopy instrumentation is still required and we will propose an innovative approach for a solution based on coupled detectors comprised of silicon photodetectors and scintillators.

In situ verification of spent fuel assemblies stored under water on stacked trays is an important safeguard task for International Atomic Energy Agency (IAEA) inspectors who are still searching for the most suitable detector solution that satisfies all the requirements of this task. This instrument is required to be small in size so as to be able fit in a confined space between bundles of irradiated fuel rods (several cm), have good spatial resolution, high count rate tolerance and relatively good radiation hardness so as to be able to work within an intensive gamma background radiation field (up to 10^5 rad/h). One of the currently used instrumentation is quite a massive system working on the detection of the high-energy prompt gamma rays from fission products (for example ^{137}Cs, 662 keV photons). The spatial resolution needed for identification of the presence of particular assembly in a bundle is achieved by heavy tungsten collimators, which are effective for gamma radiation [1].

Recently, a new approach was investigated, which utilizes Uranium fluorescent X-rays induced by prompt photons from ^{137}Cs. In this case heavy Tungsten shielding is not required since the uranium fluorescent emission is mostly in the energy range 95–110 keV. For registration of these photopeaks CdZnTe, CdTe and small Si detectors have been tested. Innovative work on the development of such CZT based, portable detector probes for these purposes was done by the Riga's group in collaboration with IAEA [2]. The advantages of CZT detectors include high photopeak efficiency ($Z = 48.5$), operation at room temperature, and good energy resolution (about 4 keV for the 122 keV ^{57}Co photopeak). For similar size of Si detectors $1\times1\times0.3$ mm^3 and the same conditions the energy resolution is about 5 keV, however the photopeak efficiency is much less than in CZT. The small size of the detectors allows for high dose rate applications in spectroscopy mode.

This method still requires Pb or W shielding for reducing the gamma ray intensity from fission products. In this case separation of X-ray fluorescence from Pb (about 80 keV) and U (about 100 keV) is required. Operation of the detectors in the intensive gamma ray background demands selection of U-peaks on a strong Compton background from the fission products. This background degrades the energy resolution of CZT mini detectors and in the case of Si detectors, observation of 100 keV energy U-X-ray fluorescence is impossible.

Another problem in determining the location of the single fuel element in a bundle through U signature is scattered high-energy photon radiation, which is additionally contributes to low energy Compton background in the detector, making spatial resolution of single fuel element determination even worse.

There is a need for a portable probe with good sensitivity and energy resolution for detection of pre-selected, low energy gamma/X-ray isotopes in high-energy photon masking of background applications for customs and other users to target isotope smuggling. The range of interest is 15–40 keV and in this case the energy resolution is the dominant parameter. A resolution of better than 2 keV is needed to prevent masking of target isotopes by more benign isotopes.

Reliable spectroscopy of single gamma lines in a mixed radiation photon field is important in nuclear medicine. The current Single Photon Emission Computed Tomography (SPECT) techniques have a significant advantage over other similar diagnostic technologies in that two or more isotopes can be imaged in parallel [3]. Simultaneous administration of ^{99m}Tc (140 keV) and the PET isotope ^{18}F (511 keV) provide ability to simultaneously image two or more physiological parameters and would represent a major advance in functional imaging, for both the clinical and basic sciences. In comparison with ^{99m}Tc only applications, this method requires much thicker collimators for 511 keV photons, with consequent reduction in active field of imaging detector. Imaging of ^{99m}Tc isotope is also degraded by the Compton background of the ^{18}F isotope. One of the solutions for this is dual mode PET/SPECT facility. A new method of detector construction for dual isotope facilities is thus also desirable.

Surgical radiation probes, which are widely applied for localization of a tumour after administration of an isotope, incorporate tungsten collimators for better localization of the isotope [4]. Non imaging probes for gamma radiation detection utilize scintillator/PMT and CZT detectors. This method is very effective for low energy isotopes (for example ^{99m}Tc, 140 keV), however with increasing photon energy the amount of scattered radiation is increasing which makes localization of the radioactivity in the body difficult. Increasing the size of the tungsten collimator is not feasible. A new design of portable radiation probes that are capable of accurate localization of activity for extended gamma energy range of isotopes is a challenge.

Development of portable probes with better spatial resolution will also be an advantage when used in the search of high-energy gamma contamination after nuclear accident. The use of a heavily collimated photodiode-scintillator detector probe within a rotated collimator was demonstrated for isotope localization in the large hall of the Chernobyl reactor after Chernobyl NP accident.

New Anti-Compton probes design

For most of the above-mentioned applications, the outcomes can be improved if an anti-Compton spectrometer is used [5]. This results in a significant reduction of the Compton contribution, leading to better identification of low energy isotopes and their localization. Most of the currently existing anti-Compton spectrometers are based on the combination of Ge and scintillator detectors. This spectrometer is bulky, demands liquid nitrogen cooling of Ge detector, and different types of front-end readout electronics for scintillator-PM and Ge detectors. The advantage of these systems is excellent energy resolution and efficiency for high-energy photons. However, they are not portable and cannot be used in safeguard applications in confined spaces or as portable probes.

We propose a design for a new class of anti-Compton detectors for portable probes for different applications. These probes we believe will better address some safeguard, security and medical applications.

Anti-Compton probes are realized on a single substrate based annular Si-photodiodes optically coupled to the annular CsI(Tl) or LYSO scintillators depending on the specific application. Fig. 1 shows a schematic diagram of one of the probes. The advantage of the probe is in identical electronics channels for readout which with a current ASIC CMOS design can be very low noise due to preamplifier with the input FET transistor attached directly to the rear side of the PD. In terms of efficiency of interaction with a photons CsI(Tl) has similar $Z = 50$ as CZT detectors and LSO has $Z = 66$. CsI(Tl) is most suitable for coupling with Si PD due to better matching of the emission spectra and photo response of the Si PD as well as the best light yield (66,000 photons/1 MeV). LYSO scintillator has less light yield (about 30,000 photons/1 MeV) and average wavelength of emitting light 420 nm that not as good a match to the Si PD but higher photopeak efficient for high energy gamma photons in comparison with CsI(Tl). Advantage of LYSO in comparison with CsI(Tl) is faster light decay, which is about 40 ns in comparison to 900 ns for CsI(Tl) scintillator.

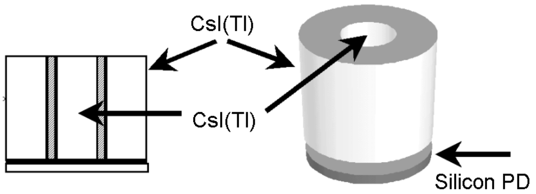

Fig. 1. Schematic presentation of anti-Compton probe. Two annular Silicon photodiodes with common rear contact and separate electrical readouts are optically coupled to optically isolated scintillators.

Another advantage that this probe is that it does not require an additional collimator. The outer scintillator has a function of the coincidence detector and high-Z wall of collimator. In this case thin aluminium shielding is feasible as usually applied for packaging of scintillators in gamma cameras. The fluorescent X-rays from Al shielding have much lower energy than the 100 keV range of interest for U X-ray signature in a spent fuel assembly. The energy resolution for ^{99m}Tc 140 keV line in the Si PD-CsI(Tl) coupled detector is 8–10 % for low size scintillator and state of the art silicon photodetector (PD) which has been designed and tested for the particular application. One of the key challenges in this project was development of the technology of manufacturing of CsI(Tl) annular scintillators and their optical isolation.

The size of the probe can be adjusted for the particular application and expected intensity of radiation field. In the case of the safeguard application the diameter of internal Si PD sensitive area will be 1.5 mm and outer PD is 4.5 mm. The disadvantage of this anti-Compton spectrometer is its low energy threshold of possible photon detection due to unity amplification of Si PD in comparison with classical Ge-BGO based anti-Compton spectrometer.

To improve the low energy response another design of spectrometer is aimed for

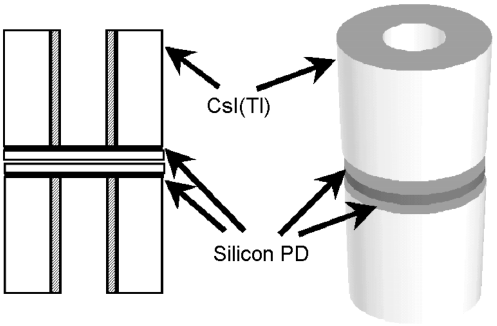

Fig. 2. Back-to-back annular Si PD with outer scintillator anti-Compton spectrometer for low energy photon detection in a mixed gamma radiation field. Combinations of the two designs with proper coincidence logic will provide a wide photon energy range, single crystal, anti-Compton spectrometer.

low energy gamma/X-ray portable probe for safeguard and other applications. Fig. 2 shows design of this probe. This probe utilizes the same type of Si PD but only one outer annular scintillator, which is covered by light reflecting paint. Advantage of this probe that the core Si detector has small area and will provide excellent energy resolution for direct events in comparison with the previous version of the probe with a scintillator core. The amplitude of the signal from the detector due to direct photoeffect of low energy U-X-ray photons in silicon will be about 4 times larger for 100 keV gamma photons than the same energy photons will provide in Si PD as a result of photoeffect in CsI(Tl) coupled to the same Si PD. However photoeffect efficiency will be much less than in CsI(Tl) core scintillator as in Fig. 1. The energy resolution for the 100 keV gamma line is expected to be about 5 keV under the room temperature operation. This approach will allow measuring U-X-ray signature in spent fuel in strong fission gamma background due to suppression of Compton contribution using the coincidence technique outlined below. The majority of scattered Compton gamma photons, originated from the high-energy photon depositing energy in Si core detector below 100 keV, will be scattered predominantly within small angles in the forward direction. To make an anti-Compton spectrometer efficient, the back-to-back connection of two annular photodiodes has been proposed (see Fig. 2). In this case Compton background suppression will be achieved in the low energy region of the Compton for isotropic, high-energy gamma scattered radiation. The annular outer scintillator will be acting, in this case, as an effective collimator and as a part of anti-Compton spectrometer. This design allows implementation of Si fast detector with the same core PD active area 1.5 mm diameter for the detection of the low energy photons in the strong gamma background. The small area of the detector will result in a detector capacitance of less than 1 pF, which guarantees good energy resolution.

Medical applications of the proposed anti-Compton spectrometer has other advantages for dual energy SPECT utilizing - ^{99m}Tc and ^{18}F isotopes with extended functional imaging capabilities. New high spatial resolution scanner will be based on pixelated Si PD array attached to pixelated scintillators as currently applied in our design of a PET scanner detector module with DOI capabilities [5]. Application of this method will provide benefit in the reconstruction of images from ^{99m}Tc 140 keV photon on the background of 511 keV gamma radiation. In this case anti-Compton spectrometer will be realized with the neighbour scintillator pixels surrounding each of the pixels.

Application of the anti-Compton spectrometer in the form of a surgical radiation probe will make this probe suitable for high-energy photons like 511 keV. This design will make the probe smaller in size and will avoid heavy tungsten collimators, which attenuate scattered radiation. The outer scintillator of probe has a dual function as a collimator and as inverse anti-Compton spectrometer, rejecting events in the core scintillator originated by photons scattered from the outer scintillator. It allows for a reduced thickness of wall and makes the probe smaller for high energy radiation and improves the spatial resolution of the probe.

Radiation testing of Si PD coupled with CsI(Tl) and LYSO for single crystal anti-Compton spectrometer

The different models of Si PD have been developed with optimised technology and coupled with CsI(Tl), LSO and LYSO scintillators and tested. Fig. 3 shows the results obtained with CsI(Tl) and LYSO scintillators for 662 keV and 511 KeV photons. Excellent energy resolution has been achieved that is suggesting feasibility of proposed technology [7, 8].

In conclusion, an anti-Compton spectrometer based on a single crystal detector and suitable as a portable probe, with multiple applications, has been proposed. This spectrometer is based on an annular dual Si PD produced on the same substrate coupled with dual optically isolated scintillators. Variation of the geometry of the spectrometer makes it useful for safeguard application to measure X-ray signature of Uranium in strong gamma fields of fission products of spent fuel. Low energy photon spectroscopy is also feasible in the presence of masking gamma fields. In this case utilization of good energy resolution of Si detectors and their reasonable efficiency for low energy X-rays (~ 30 keV) in combination with outer CsI(Tl) scintillator will provide a portable anti-Compton probe. Application of the proposed approach can provide benefit in improved localization of radiation activity in a medium with high-energy gamma isotopes. Particularly it is useful for radiation probes for utilization in nuclear medicine.

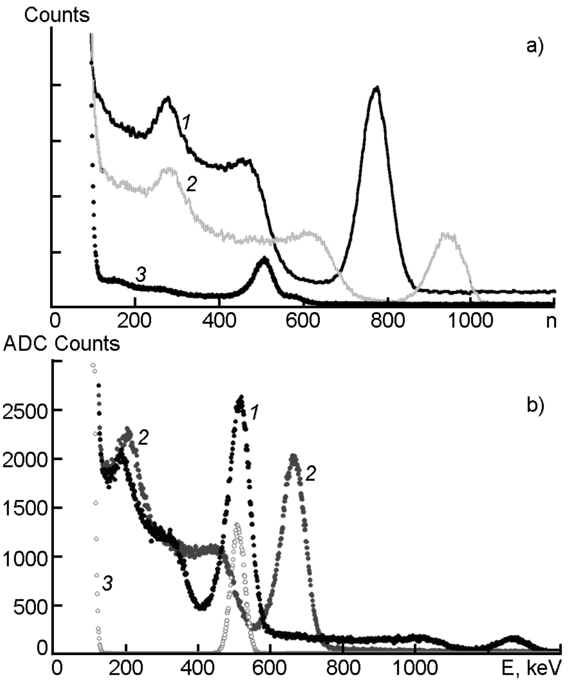

Fig. 3. Room temperature spectra of gamma radiation obtained with Si PD coupled with CsI(Tl) —(*1*), LSO —(*2*) and LYSO —(*3*) scintillators.

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Единий детектор — подвійний сцинтилятор для антикомптонівських пробників

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Антикомптонівська спектроскопія має безліч застосувань в ядерній медицині, системах контролю та огляду. Однією з найбільш важливих рис цього методу є можливість визначення низькоенергетичних гама-квантів на фоні високоенергетичних, або виділення джерел високоенергетичних часток із широкого радіаційного фону. В багатьох випадках класичні антикомптонівські спектрометри застосовуються обмежено через розміри детектуючих систем. В межах цього дослідження розроблено спектрометр, на основі подвійного кремнієвого фотодіода складної форми, зістикованій з двома призменими сцинтиляційними кристалами. Дослідження при кімнатній температурі показали працездатність детектуючої системи для випадків використання сцинтиляторів CsI(Tl) та LYSO. Отримані значення енергетичного розріжнення складають 12% та 8% (511 кеВ, 22Na) для LYSO та CsI(Tl), відповідно. Обговорюються різні варіанти Si-CsI(Tl) пробників.