APPLICATIONS OF PLASTIC SENSORS

[1]A.A.BAYRAMOV, [2]R.M.SARDARLY

[1]Academician G.M.Abdullyev Institute of Physics NAS of Azerbaijan

Baku 1143, Azerbaijan

[2]Institute of Radiation Problems NAS of Azerbaijan

Məqalədə plastik detektorların müxtəlif radiasiya ölçülərda istifadəsi haqqında, o cümlədən antiterror məqsədlə, qısa icmal verilir. Plastik sinsilyatorlar praktikada laboratoriya və çöl şəraitində isitifadə olunur gamma-radiasiya monitoring üçün, real zaman şəraitində radioizotopların təini üçün və skrining əməliyyatı aparan zamanı. Kiçik ölçülü plastik detektorların müxtəlif radiasiya məmbələrə statik və dinamik həssaslıqını nəzərdən keçilirir.

В статье дается краткий обзор применения пластических сенсоров в различных радиационных измерениях, включая в антитеррористических целях. Пластические сцинтилляторы используются в практических целях в лабораториях и полевых условиях для гамма-радиационного мониторинга, определения радиоизотопов в реальном режиме времени и при скринировании. Рассматривается статическая и динамическая чувствительности гамма измерений малого размера пластических детекторов к отдельным источникам радиации.

A brief survey of plastic scintillators and sensors for various radiation measurement applications (including antiterroristic) is presented in the paper. The utility of plastic scintillators for practical applications such as gamma radiation monitoring, real-time radioisotope detection and screening is evaluated in laboratory and field measurements. Small-size plastic detectors are evaluated for static and dynamic gamma-ray detection sensitivity of selected radiation sources.

1. BACKGROUND

Organic scintillators in the form of solid, machinable plastic materials have long been an inexpensive source of radiation detector material. Plastic scintillators were first produced around 1950 in order to extend the developing liquid scintillator technology to that of a solid-phase medium. Plastic scintillators are characterized by the presence of a benzene ring structure in the constituent molecules. Plastic scintillators are solid solutions consisting of organic fluorescent compounds dissolved in a solidified polymer matrix [1-5]. Most of the plastics used for light scintillation purposes are polystyrene (polyvinylbenzene) and polyvinyltoluene (polymethylstyrene). A variety of plastic scintillators has been developed to meet detection requirements [6].

Two plastic scintillators manufactured by Saint-Gobain Corporation, BC-400 and BC-404, have been in extensive general-purpose use for more than three decades. The BC-408, BC-412 and BC-416 plastic scintillators have almost 100% transparency for their own scintillation light and are used when the length of the scintillator exceeds 75 cm. The BC-454 contains a high concentration of enriched 10B5 for thermal neutron detection purposes. Light output of 5% boron-loaded BC-454 is 48% that of anthracene. A slow neutron reacts with the boron inside the plastic material in the following way: $^{10}B_5 + n \rightarrow {}^{7}Li_3 + {}^{4}He_2$.

The BC-418, BC-420 and BC-422 plastics have exceptionally short scintillation time constants, making them particularly useful for counting at extremely high rates or for high-precision coincidence counting. The BC-428 and BC-430 plastic scintillators have fluorescent spectra at longer wavelengths than do the other scintillators for spectral light collection applications. The BC-434 and BC-438 plastic scintillators have been formulated for use at higher temperatures. Some of the plastic scintillators contain lead or tin to enhance sensitivity to x-rays while another special scintillator, BC-470, is formulated to have a flat response to x-rays and gamma rays, making it useful for dosimetry. Two new developments are BC-444, which is unique among the many plastic scintillators in that its fluorescence decay time is relatively long, and BC-454, which contains boron for special neutron detection purposes. Most of these plastic scintillators have narrow areas of application; the general-purpose types such as BC-400, BC-404 and BC-408 comprise more than 80% of the plastic scintillators produced.

Large volumes of radiation-hardened plastic scintillators are used as charged-particle calorimeters for hadron physics. The Thomas Jefferson Laboratory has chosen 4 m-long BC-412 plastic plates to build the calorimeter for the Large Acceptance Spectrometer [7]. The fast rise time (2-3 ns) of the scintillating pulses makes plastic scintillators attractive for timing purposes. Timing resolutions of a few hundred picoseconds are routinely achievable. Thick (20-cm) "walls" of large-area (1 m^2) plastic scintillators are used to detect energetic neutrons via knockout reactions; namely, $^{1}H(n, p)$ and $^{12}C(n, p)$ taking place inside the volume of the plastic scintillator [8].

Recently, compact neutron coincidence spectrometers have been patented [9]. The coincidence unit is made up of a 1000 cm^3 of plastic scintillator cylinder segmented and separated equally by three ^{6}Li-glass plates. Signals from the ^{6}Li plate represent thermal neutrons and indicate absorption of the energetic neutron in one of the four plastic segments. Because of low density and low atomic number, plastics cannot be used for energy spectrometry, and their intrinsic efficiencies are somewhat lower than those of inorganic scintillators. However, taking advantage of the large sizes and variety of shapes available, plastic scintillators are used for many gross gamma counting applications. They are extensively used as active sensor elements in walk-through and vehicle portal monitors for contamination detection and nuclear safeguard applications. Other uses include factory waste survey systems, laundry monitors and whole-body counters. Gamma portal monitors, typically used at a nuclear

facility exit gate where all people either enter or leave the facility, use plastic scintillators to identify any inadvertent passage of radionuclides emanating gamma rays.

2. PROPERTIES OF PLASTIC MATERIALS (SCINTILLATORS)

Inorganic crystalline scintillators such as sodium iodide (NaI), bismuth germanate, $Bi_4Ge_3O_{12}$ (BGO) and cesium iodide (CsI) are conventionally used in gamma-ray spectroscopy for their linear response, enormous light output (a factor of 4 better than a plastic scintillator), relatively higher absolute scintillation efficiency (~12%) and good energy resolution. Plastic scintillators have so far been ignored in field applications for gamma-ray measurements, even though they have some practical advantages over inorganic scintillators in terms of being less dense, less expensive, less temperature sensitive, rugged and are manufactured in large machinable volume. Plastic scintillators enjoy the unique advantage over NaI(Tl) that they have usable neutron response. The neutron detection efficiency (~8-12%) is dependent on the energy, threshold, thickness and volume of the plastic scintillator used. Neutron pulses are slower than gamma scintillator pulses and are easily separable in liquid scintillators. Characteristic physical properties of some common scintillator materials are listed in Table 1 below.

Table 1: Properties of scintillators

Material	Density (g/cc)	Wavelength of maximum emission, nm	Refractive Index	Principal Decay Constant (m-Sec)	Total Light Yield	Pulse Rise Time (msec)	Absolute Scintillation Efficiency	Relative Pulse Height
NaI(Tl)	3.67	415	1.85	0.23	38000	0.5	11.3	1.00
CsI(Tl)	4.51	540	1.80	1.0	52000	4.0	11.9	0.49
LiI(Eu)	4.08	470	1.96	1.4	11000		2.8	0.23
BGO	7.13	505	2.15	0.30	8200	0.8	2.1	0.13
BC-400	1.032	423	1.58	0.02	10000		3.0	0.25
BC-454	1.026	425	1.58	0.0022	10000		3.0	0.25

The ideal scintillator should possess the following properties:

· It should convert the kinetic energy of charged particles into detectable light with high scintillation efficiency;

· The conversion should be linear; the light yield should be proportional to deposited energy over as wide a range as possible;

· The medium should be transparent to the wavelength of its own emission for good light collection;

· The decay time of the induced luminescence should be short so that fast signal pulses can be generated;

· The material should be of good optical quality and subject to manufacture in sizes large enough to be of interest as a practical detector;

· Its index of refraction should be near that of glass (~ 1.5) to permit efficient coupling of the scintillation light to a photomultiplier tube.

Only a small fraction of the kinetic energy lost by a charged particle in a scintillator is converted into fluorescent light. The remainder is dissipated nonradiatively, primarily in the form of lattice vibrations and heat. The fraction of energy that is converted into fluorescence energy (scintillation efficiency) depends on the particle type and its energy. For organic scintillators such as anthracene, stilbene and other commercially available plastic scintillators, the response to electrons is linear for energies above 125 keV. The response to heavy charged particle like protons or alpha particles is always less for equivalent energies and is nonlinear to much higher initial energies.

The light output of a scintillator depends on its efficiency for conversion of ionization energy to photons. The light output determines the efficiency and resolution of the scintillator. In general light output is different for different types of particles at the same energy. A given particle type does not always vary linearly with energy. Average energy losses required for creation of a photon for different materials by electron excitation are listed in Table 2.

Table 2: Average energy loss per scintillator photon for electrons

Materials	**eV/Photons**
Anthracene	60
NaI	25
BC-400	100
BGO	300

Two types of efficiencies relate to the discussion of gamma-ray detectors. Absolute efficiency is the ratio of the number of pulses recorded to the number of radiation quanta emitted by source. Intrinsic efficiency is defined as the ratio of the number of pulses recorded to the number of quanta incident on the detector. For an isotropic source, the two efficiencies are related by a solid angle subtended by the detector at the source.

$$\varepsilon_{int} = (4\pi/\Omega)\varepsilon_{abs},$$

where Ω is the solid angle of the detector at the source. To describe a relative percentile efficiency of gamma detection of plastic scintillators compared to that of NaI(Tl), one defines a term

$$A_{eff} = 100\,(1 - \exp(-\mu L)),$$

where A is relative efficiency, μ is linear attenuation constant for the specific materials and L is the length traveled inside the specific medium. See Table 3. It is noteworthy that for the same values of A_{eff}, the ratio, L_{NaI}/L_{pl}, increases with increasing values of E_g and is 0.27 at 400 keV. In the energy region of interest (60 through 3000 keV), the gamma-ray detection efficiency of plastic scintillators relative to that of NaI can be approximately given by (30 ± 3)%.

Table 3: Required distance traveled (L, cm) as a function of g-energy (Eg , MeV) for selected relative efficiency (A_{eff})

A_{eff}	50%		70%		90%	
Eγ	L_{NaI}	L_{pl}	L_{NaI}	L_{pl}	L_{NaI}	L_{pl}
0.8	0/07	3.8	0.11	6.7	0.21	12.7
1.0	0.12	4.0	0.21	7.0	0.39	13.4
0.2	0.61	4.9	1.1	8.5	2.0	16.2
0.3	1.2	5.6	2.1	9.7	4.0	18.6
0.4	1.7	6.3	2.9	10.9	5.6	20.8
0.5	2.1	6.8	3.6	11.9	6.8	22.7
0.6	2.4	7.4	4.1	12.9	7.8	24.6
0.8	2.9	8.4	5.0	14.7	9.5	28.0
1.0	2.3	9.4	5.7	16.3	10.8	31.2
1.5	4.1	12	7.0	20/1	13.5	38.4
2.0	4.6	14	8.0	23.5	15.2	45.0
3.0	5.2	17	9.0	29.9	17.2	57.1

3. PLASTIC NEUTRON DETECTORS.

The BC-720 is a scintillator designed specifically for detecting fast neutrons while rejecting gamma radiation in a mixed radiation field. It consists of zinc sulfide (silver) (ZnS[Ag]) phosphor embedded in a clear hydrogenous plastic material; it functions by means of a proton recoil interaction in the scintillator, the proton being detected by the zinc sulfide. The detector is a 15.9 mm thick plastic disc, which can be mounted directly to photomultiplier tubes or to light guides using a variety of optical greases or epoxies. It is best used with photomultiplier tubes with high blue sensitivities such as those having bi-alkali, S-20 or S-11 type photocathodes. The gamma discrimination capability provided by the BC-720 is of particular value. The gamma pulse height is usually less than the neutron pulse height; in gamma fields below 1R/hr, the gamma rays can be easily rejected by pulse height discrimination. However, due to the random generation of recoil protons throughout the detector, the neutron spectrum is quite broad. In high gamma fields, the simultaneous detection of two or more gamma rays could produce pulse heights falling within the lower energy portion of the neutron spectrum; the use of a lower discriminator for gamma rejection would reduce the neutron detection efficiency. Gamma rejection may also be achieved by the use of time constants of a few microseconds.

4. POLARIZABLE PLASTIC DETECTORS.

Polarized scintillating targets are now routinely available [10]. New possibilities for the measurement of spin-dependent observables in nuclear and particle physics are offered by the development of polarizable plastic detectors. A polarized scintillating target is an instrument in which the hydrogen nuclei in a piece of scintillator can be dynamically polarized at very low temperatures and the light produced in the scintillator by scattered particles can be forwarded to a photomultiplier at room temperature.

5. RADIATION RESISTANCE OF PLASTIC DETECTORS

To examine the radiation hardness of plastic materials used in large hadron calorimeters, the Zeus experiment group irradiated small plastic samples with gamma rays and neutrons at external locations (HMI Berlin, GKSS-Research Reactor Geesthacht) [11]. The radiation damage in polymeric material, often found to be receding, is somehow linked to the diffusion of oxygen. The Zeus group at CERN (European Organization for Nuclear Research) developed an apparatus especially to examine these effects. The group has developed a diffusion model, which described the recession of radiation damage during and after irradiation and was able to make quantitative predictions of radiation damage in the Zeus detector during ten years of operation. The working group was able to prove that irradiation produced short-lived absorption centers in some scintillator materials, which disappeared after a few hours. These absorption centers did not cause permanent radiation damage; however, recalibration of the detector was necessary.

6. ALPHA AND BETA DETECTION

Thin sheets and films of BC-400 and BC-434 are routinely used in survey instruments and for reactor gas monitors. Thin films are also used in beta dose detectors since the plastic materials are tissue equivalent to beta particles. Thus films and tiny spheres are used in constructing flow cells for monitoring beta activity in reactor cooling water. Since alpha particles have a limited range in air (approximately 2.5 cm), a typical application, such as the Flow-Through Alpha Monitor would use a detector with multiple (~16) plates. Using multiple plates has two other important advantages. First, it provides built-in redundancy. If one plate were to fail, only a portion of the detector would cease operation. Second, multiple plates allow one to distinguish between alpha events and natural background such as cosmic rays. The scintillating plates are made of a common plastic base, with a special scintillating chemical additive. For alpha detection, the Flow-Through Alpha Monitor system uses sheets of scintillator that are 30.5 x 30.5 cm with a thickness of 1 mm or a detector area of 1860 cm^2 on a single plate. One can add to the detector plates that are optimized for detecting more penetrating forms of radiation, such as beta or gamma rays. These plates are thicker, typically 13 mm.

7. PLASTIC ALPHA-TRACK DETECTORS AND RADIONUCLIDE MAPPING.

The physical location of radioactive contaminants in soils is an important factor in understanding the contaminant migration mechanisms and in the estimation of models parameters. The common approach in parameter estimation is the assumption that the radionuclides are homogeneously distributed either uniformly or with some exponential depth profile under the ground surface. In addition, data analysis is frequently done on homogenized samples. Soil, however, consists of various size clay, sand, rock etc. particles bonded together by organic and inorganic materials. Autoradiographic method is used to identify both the distribution of selected nuclides along key structural features of sampled soil and the size of "hot particles" of the contaminants. This autoradiographic method includes contact autoradiography with CR-39 plastic alpha-track detectors (Homalite Plastics) and neutroninduced contact autoradiography that produced fission fragment tracks in Lexan (Thrust Industries, Inc.) plastic detectors.

Autoradiographic methods using plastic alpha-track detectors allow to associate the location and the size of alpha-emitting particles of contaminants with key morphological features of a soil sample. The combination of two autoradiographic methods allowed the determination of $^{239}PuO_2$ particles as small as 0.08 μm after 715 hours of exposure time; to distinguish alpha-stars caused by natural uranium particles, and particles of fissile and non-fissile actinides.

8. PLASTIC DETECTORS FOR HIGH GAMMA DOSE MEASUREMENTS

It is important to measure the absorbed gamma doses in (a) nuclear reactor structural materials and (b) electronic components. Gamma measurements are also required during the gamma sterilization of different medical products and in food preservation. Such measurements are difficult to be made in situations such as in and around a reactor core, where besides the presence of high fluxes of neutrons, exist elevated temperatures.

Some efforts have already been made to develop solid state materials for the determination of high gamma doses. The limited experience gained from the use of solid state nuclear track detectors for high gamma dosimetry clearly confirmed that these detectors show a great promise for such an application. Particularly, the composition of plastic track detectors favors their use for in-core gamma dose measurements in water cooled and water moderated reactors, where the compositions of the detectors and of the surrounding environments are comparable.

Another advantage of plastic track detectors is their use in the study of biological samples, where the equivalent compositions of the detecting and the surrounding materials produce an edge over other type of detectors in such applications. It may be mentioned at this juncture that the commonly available plastic track detectors have an added advantage of exposure conditions. They can be safely lowered into the water pool and can be held at definite positions with the help of simple tools.

9. ALPHA SPECTROMETRY BY MEANS OF PLASTIC DETECTOR CR-39

There is new technique of alpha spectrometry with usage of solid state plastic track detectors, based on application of artificial neural networks. A neural network of opposite propagation is applied for tracks images recognition which is obtained by optical microscope. Presented approach is very perspective alternative of tracks discrimination as the traditional methods of shapes algorithmization are too complicated and dependent on scanning conditions.

10. APPLICATION OF CR-39 PLASTIC DETECTOR IN COLD FUSION EXPERIMENTS.

The problems of identification of different particles and background/foreground separation are very important in cold fusion experiments. CR-39 plastic track detector, which is used for registration of heavy charged particles, is a very convenient means of detection not only dd-fusion reaction products:

$$d + d \rightarrow n\ (2.45\ MeV) + {}^3He\ (0.82\ MeV)\ (\sim 50\%) \quad (1)$$

$$d + d \rightarrow p(3.02MeV) + T(1.02MeV)\ (\sim 50\%) \quad (2)$$

but also dT ones:

$$d + T \rightarrow n\ (14.01\ MeV) + {}^4He\ (3.5\ MeV) \quad (3)$$

This detector has characteristic response to every type of particles from reactions (1) - (3). Charged particles are registered directly, and neutrons are detected through the secondary recoil particles or nuclear reactions. Particle tracks on the detector became visible after etching and are investigated using a microscope. The goal of present work is to study the CR-39 detector response using different types of particles from reactions (1)-(3) in different experimental conditions.

The CR-39 plastic track detector is a $C_{12}H_{18}O_7$ polymer with density 1.3 g/cm^3. After exposure, the detector was etched in ^{6}N NaOH solution at 70°C for 7 h. After the etching, charged particle tracks became visible and could be investigated using a microscope.

As is well known, the main parameter of track detector is the ratio of etching rates at the start of the track and at the end of the track (v_T/v_B). This ratio is a function of energy loss (stopping power, *dE/dx*). Track diameter is related to this ratio by a parametric equation. The dependence of track diameter on *dE/dx* makes possible identification of a particle. The critical angle of registration ($\Theta_c = \arcsin(v_T/v_B)$) is also an important characteristic. Θ_c is the minimum angle of particle incidence on the detector in which track formation is possible. It is easy to show that the detection efficiency for a given type of particles is determined by the relation:

$$\eta = 1 - \sin \Theta_c \quad (4)$$

It is established that CR-39 track detector can detect all particles from reactions (1) - (3). This detector can be successfully used in long-duration experiments in cold fusion.

11. PORTABLE PLASTIC EXPLOSIVES SENSORS FOR ANTITERRORISTIC APPLICATIONS

In 2001, Richard Reid boarded an American Airlines flight with plastic explosives inside his shoes. Since then, Americans have had to remove their shoes during airport

security checks and, at some airports, go through an air puffer that uses spectrometry to check passengers for traces of explosives. A new, easy to use explosives detector developed by RedXDefense of Rockville, MD, could provide a quick, simple visual diagnostic for the plastic explosives favored by terrorists like Reid. The device is portable and designed for use by nonscientists at security checkpoints and under harsh conditions. The detector is currently undergoing field tests in Iraq.

"Most explosives-detection methods go after sensing vapors," says William Trogler, a chemistry professor at the University of California, San Diego, who developed the technology behind the device. This works well for detecting buried land mines and other devices that use volatile explosives, such as TNT, that form a gas that can be detected in the air. But the plastic explosives often used by terrorists are not very volatile, and technologies for their detection usually require dislodging the explosive from a surface, such as with a puff of air, before running a chemical analysis. And these systems are not portable.

Trogler developed a sprayable polymer that fluoresces blue-green under ultraviolet (UV) light, unless in the presence of explosive molecules, including PETN and TNT, that turn off this fluorescence. When the polymer is sprayed on a surface and examined under UV light, explosives appear as black spots.

The product, called the XPak, consists of a plastic viewing box and a removable baton that resembles a lint roller. First, the soldier or police officer using the device rolls the paper-covered baton over the surface to be tested or has the subject being screened grip the roller with his hand. The baton is then placed inside the viewing box, where it is sprayed with the luminescent polymer. The user then looks through the viewfinder and employs a knob to rotate the baton under UV light. If there are no explosives present, the baton will look entirely blue. Wherever there are traces of explosives, even as small as a few picograms, there will be black spots.

Trogler says that the advantage of this system is that the results can be interpreted visually by nonscientists. "This is intuitive," he says. "The human eye is very good, and you don't have that overhead" of image-analysis software or spectrometry.

CONCLUSION

A brief survey of plastic scintillators and sensors for various radiation measurement applications (including antiterroristic) is presented in the paper. The utility of plastic scintillators for practical applications such as gamma radiation monitoring, real-time radioisotope detection and screening is evaluated in laboratory and field measurements. Small-size plastic detectors are evaluated for static and dynamic gamma-ray detection sensitivity of selected radiation sources.

Plastic scintillators are used in multiple radiation detection and measurement systems under diverse experimental conditions, because of their light weight, large area, considerable light output, radiation hardness and polarizability. For safeguard applications, plastic scintillators can be used in portal and vehicle monitors. Even though plastic scintillators have significant non-linearity in their light output (so no spectral information can be obtained from gamma radiation) for non-spectroscopic gamma detection work, plastic scintillators are better than inorganic scintillators.

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