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Application of Optical Fiber in Radiation Detection Systems

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Abstract: In the last years, the production of optical fibers cables has made possible the development of a range of spectroscopic probes for in situ analysis performing beyond nondestructive tests, environmental monitoring, security investigation, application in radiotherapy for dose monitoring, verification and validation. In this work, a system using an optical fiber cable to electromagnetic signal transmission from a NaI(Tl) radiation detector is presented. The innovative device takes advantage mainly of the optical fibers large passband, small signal attenuation and immunity to electromagnetic interference to application for radiation detection systems. The main aim was to simplify the detection system making it to reach areas where the conventional device cannot access due to its lack of mobility and external dimensions. Some tests with this innovative system are presented and the results stimulate the continuity of the researches.

Key words: NaI(Tl), optical fiber, radiation detection, scintillator.

1. Introduction

In the last years, research groups have dedicated efforts to the development and use of coupling OF (optical fibers) to spectroscopic instrumentation for several types of applications [1]. In this work, the purpose is to use an OF cable in a radiation detection system to allow more flexibility in in situ analyzes using the EDXRF (energy dispersive X ray fluorescence) technique. To perform nondestructive analysis, using the EDXRF technique, is necessary to use a system consisting of a radioactive source for the excitation of the sample and a detector to identify the characteristic X rays emitted by the sample. Generally, the detector is of type Sodium Iodide activated with Thallium, the NaI(Tl). Moreover, it is necessary the associated electronics (photomultiplier (PM) tube, preamplifier, amplifier, high voltage source) and a multi-channel system for processing data that records the characteristic spectrum obtained. The PM tube and the NaI(Tl) crystal are generally coupled each other. The light created by the process of scintillation when radiation interacts with the sensitivity volume of the crystal is directly transmitted to the PM tube that, after the photoelectric process, produces an electrical current pulse proportional to the incident radiation.

The EDXRF technique is very applied to several investigations, for example, for the determination of the nature, structures and components of works of art [2-4]. For in situ analyzes, it is necessary to have a portable system. In the conventional system, the detector and the PM (photomultiplier) tube are coupled as it is possible to see in the Fig. 1 at left side. The idea was then to construct an innovative device for decoupling detector and PM in such way that both constitute only one body but connected each other by an optical fiber cable allowing more flexibility mainly to in situ measuring. In this case, the OF cable works as a remote probe transmitting the light signal generated by the NaI(Tl) detector to the PM tube.

In the scintillation mechanism, the absorption of energy by the crystal results in the elevation of an electron from its normal position in the valence band across the gap into the conduction band, leaving a hole

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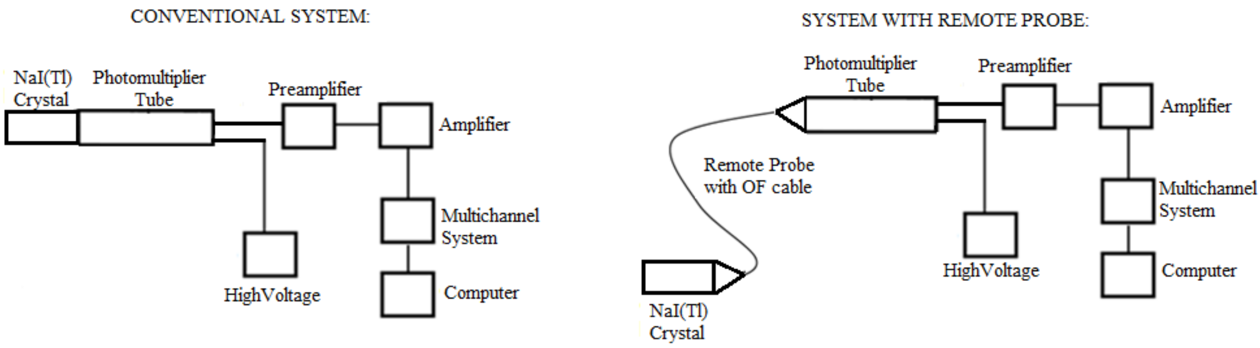

Fig. 1 EDXRF system. Left side: conventional system with coupled crystal and PM tube. Right side: decoupling of the crystal and the photomultiplier tube by the use of an OF cable remote probe.

in the normally filled valence band. The probability of visible photon emission is increased adding small amounts of an impurity (activator) to the crystal and creating energy states within the forbidden gap through which the electron can de-excite back to the valence band. This transition can give rise to a visible photon being the basis of the scintillation process [5].

In addition, to convert the extremely weak light output of scintillation pulse into a corresponding electrical signal, it is necessary the use of a PM tube that converts light signals typically of no more than a few hundred photons into a usable current pulse [5]. In the conventional detection systems, the crystal is directly coupled with the PM tube as shown in the Fig. 1 (left side). Therefore, the purpose of the innovative system, described in the next section, is to promote the decoupling of the crystal and the PM tube, connecting them through an OF cable. However, it is necessary to perform several tests to verify the adequate transmission of the light to the PM tube. This innovation simplifies the detection system, once it could reach areas for application that the conventional device cannot access due to its lack of mobility and its external dimensions.

2. Materials and Experimental System

In the proposed system, an optical fiber cable works as a remote probe being connected in one side to a NaI(Tl) detector and in the other side to a PM tube as it is shown in the Fig. 2. It was used a Chinese cable model Step Index Multimode with band range from 400 to 1,440 nm, diameter of 4 mm and length of 2 m. In the ends of the OF cable there are conical adaptors, dark painted, and each one has an adjustable system of converging lenses that focuses the light signal from the crystal detector to the optical fiber. Into the fiber, the light signal travels through by total reflection, reaching the other extremity of the probe and being focalized and distributed throughout the surface of the PM tube.

Two plane-convex converging lenses, Lens 1 and Lens 2 in the Figs. 3 and 4, respectively, were used to compose the remote probe. They have 6.4 and 3.2 cm of diameter, respectively, and were specially fabricated with the function of focuses the light beam from the detector to the optical fiber and to allow, in this way, the signal transmission until the PM tube. These lenses are designed for infinite conjugate (parallel light) use or simple imaging in non-critical applications and they are ideal for all-purpose focusing elements and then are used in this work to focusing the light to the optical fiber.

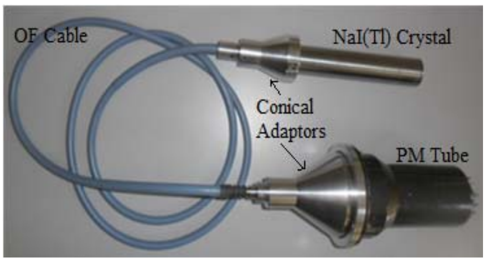

Fig. 2 FO cable connecting the PM tube with the NaI(Tl) crystal.

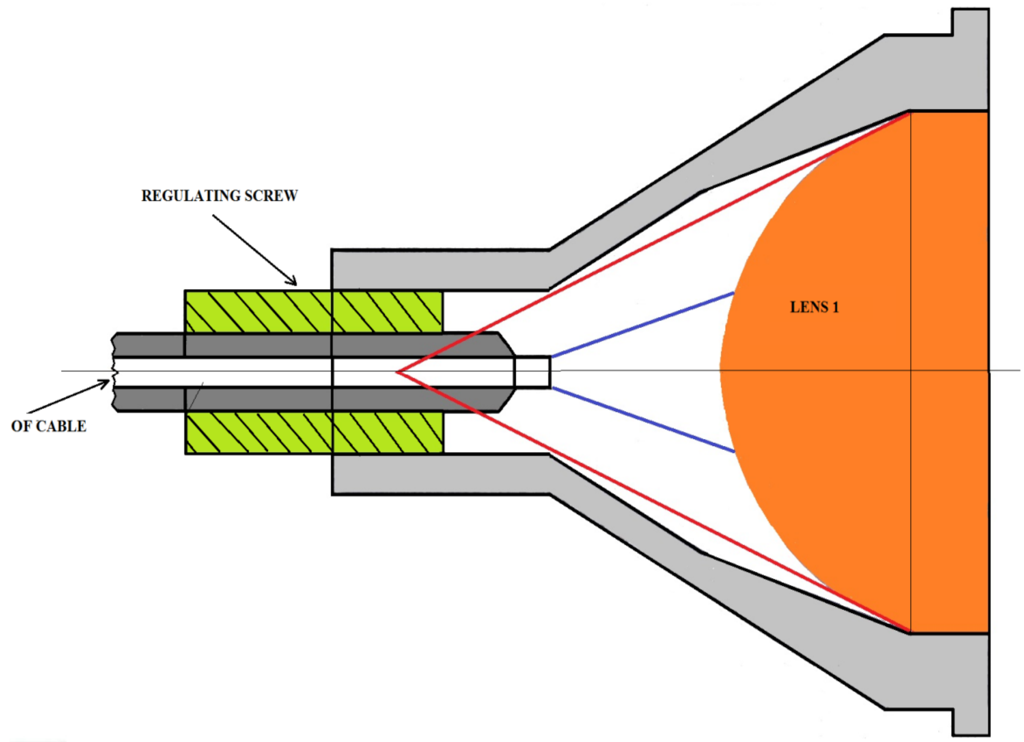

Fig. 3 Maximum capture of the light from the OF (in blue) and guided to the PM tube. The PM is coupled at the right of the Lens 1.

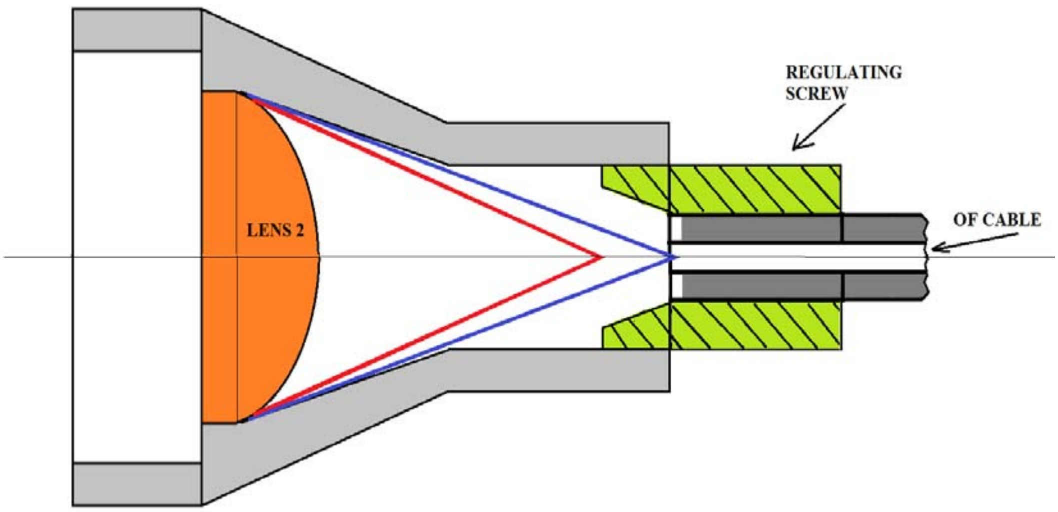

Fig. 4 Captation of the light coming from the crystal (beam in blue) guided to the OF. The crystal is coupled at the left of the Lens 2.

In the fabrication of both lenses, the diameters of the crystal and PM tube were considered. The focal length was dimensioned in accordance with the acceptance cone of the optical fiber. The ideal case would be that the optical cones of the lenses coincide with the acceptance cone of the OF. However, due to manufacturing difficulties, measurements were approximate. Thus, the solution to maximize the capitation and emission of the light was to design regulating screws (see Figs. 3 and 4) which allow approach or spacing between the lenses and the OF causing, at one end, the highest light signal from the crystal detector to the FO and, at the opposite end, maximization of the light signal emitted by the FO to the PM.

3. Tests and Results

Firstly, the acceptance cone of the OF was verified. Then, tests using an X ray and an ^{241}Am sources were performed to verify the radiation signal transmission from the crystal detector up to the PM tube after crosses the OF cable.

3.1 Acceptance Cone of the OF

The first test realized was the measuring of the acceptance cone of the OF. For this test, a device was constructed with base and supports of wood, a goniometer, a light meter (MLM 1011 - Minipa) and a mini-laser, as it can be seen in Fig. 5. The light meter is capable to measure from 1 to 1 × 10^5 lux. The procedure was to fix the mini-laser on the mobile goniometer axis with the laser pointing to the face of the OF, centered on the same. Then, by varying the incidence angle of the laser, the corresponding luminance was measured. The result of this experiment can be seen in the graph of Fig. 6. As it is possible to observe, the maximum illuminance verified was (23.6 ± 0.1) × 10^1 lux for a laser incidence angle of (90.0° ± 0.5°) to the cross-section area of the OF window, as it was expected.

3.2 Test for Light Transfer Verification by OF Cable

This test was performed irradiating the NaI(Tl) crystal perpendicularly with X rays from a mobile device type Aquilla Plus-VMI. The light meter was used to verify the signal transmitted through the OF cable (Fig. 7). This test was performed, firstly, using a digital camera in the place of the light meter to visualize the produced images and the results were published in a preceding work [7]. In the present test, two types of detectors are used and the voltage of the X ray equipment is gradually increased. The test purpose is to verify that the output signal by SR behaves as expected. After the X ray reaches the crystal, the phenomenon of the scintillation occurs and a light signal is generated by the crystal.

The X ray voltage was varied from 60 to 120 kVp. The conditions for all tests were:

- X ray tube current = 50 mA;
- exposure time = 1.5 s;
- distance between the focus and the geometric center of the detector = 20.0 cm;
- optical window of the light meter and the lens of the probe in direct contact.

Fig. 5 Apparatus to OF acceptance angle measurement.

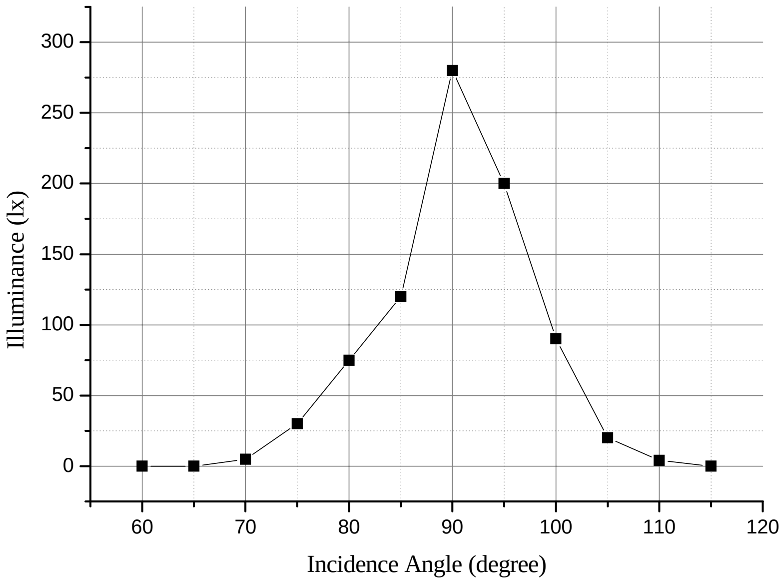

Fig. 6 Illuminance measured at the output of the OF as a function of the incidence angle of the laser in the cross-sectional area of the OF input window.

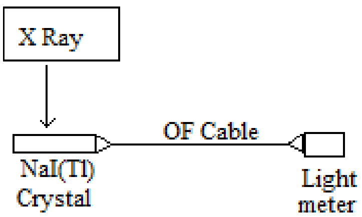

Fig. 7 Experimental scheme to verify the transmission of the light generated in the NaI(Tl) crystal as function of the X ray incident.

The detector characteristics used are:

D-I: NaI(Tl) Detector; Optical window area: 9.68 cm^2; Sensitivity Volume: 225.16 cm^3

D-II: NaI(Tl) Detector; Optical window area: 5.15 cm^2; Sensitivity Volume: 23.27 cm^3

Four illuminance measurements were performed for each voltage value of the X ray equipment, and the average value was calculated for each case. Table 1 and Fig. 8 present the results. As it was expected, the detector D-I with sensitivity volume higher in relation to D-II, presented higher illuminance signals output.

3.2.1 Results Analyses

Through a polynomial regression of the curve relative to the detector D-I of Fig. 8, relations between the voltage V applied to the X ray machine and the value of the illuminance measurement were found. The graph of Fig. 9 shows the regression equation with the values of the parameters:

$$Y = B + B_1X + B_2X^2$$

According with the Fig. 9, the parameters are:

$$B = 4133.067$$

$$B_1 = -197.173$$

$$B_2 = 2.376$$

Therefore, the equation is

$$\text{Illuminance} = 4133.067 - 197.173V + 2.376V^2,$$

where V is the voltage in kVp and the illuminance value is given in lux.

Table 1 Variation of the illuminance value with the X ray voltage for two types of detectors.

Case	Voltage (kVp)	Average Illuminance ($\times 10^1$ lux)	
		D-I	D-II
1	60.0	90.0 ± 0.1	20.0 ± 0.1
2	65.0	140.0 ± 0.1	30.0 ± 0.1
3	70.0	190.0 ± 0.1	5.0 ± 0.1
4	75.0	270.0 ± 0.1	80.0 ± 0.1
5	80.0	350.0 ± 0.1	120.0 ± 0.1
6	85.0	450.0 ± 0.1	180.0 ± 0.1
7	90.0	560.0 ± 0.1	250.0 ± 0.1
8	95.0	690.0 ± 0.1	340.0 ± 0.1
9	100.0	820.0 ± 0.1	440.0 ± 0.1
10	105.0	970.0 ± 0.1	550.0 ± 0.1
11	110.0	1120.0 ± 0.1	690.0 ± 0.1
12	115.0	1290.0 ± 0.1	830.0 ± 0.1
13	120.0	1460.0 ± 0.1	980.0 ± 0.1

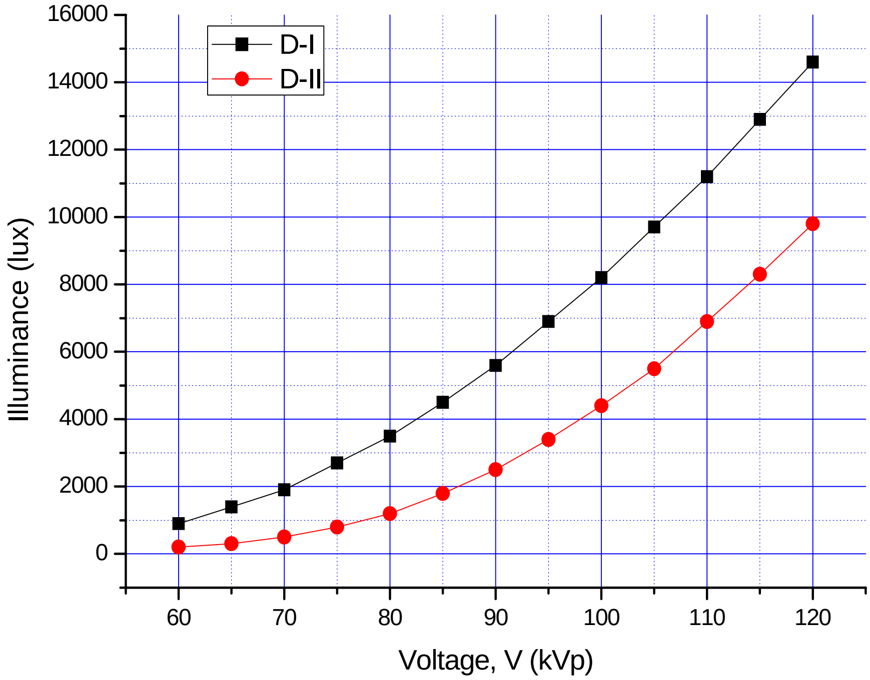

Fig. 8 Test with the remote probe: illuminance variation with the kilovoltage applied to the X ray equipment for detectors D-I and D-II.

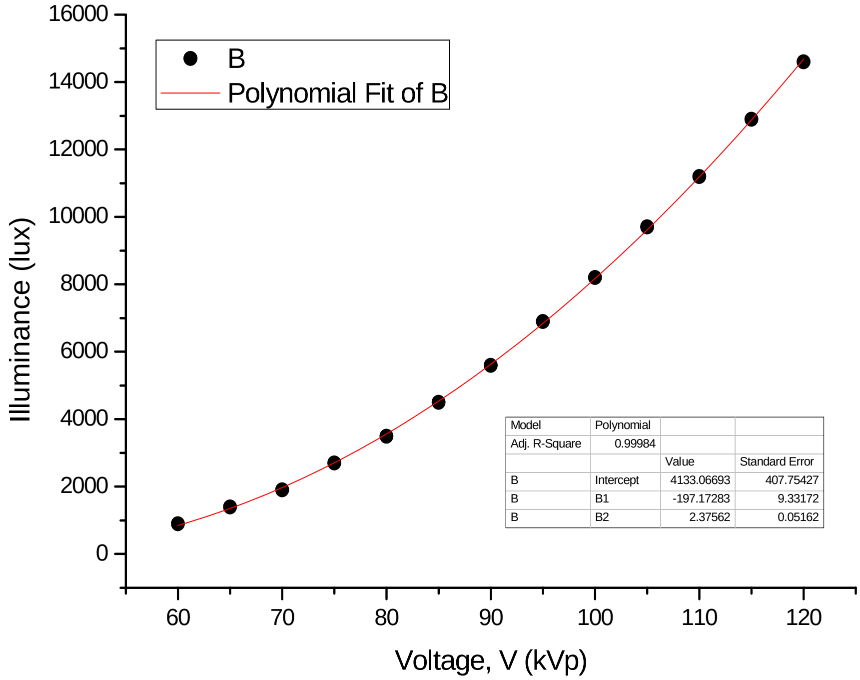

Fig. 9 Illuminance variation with the voltage applied to the X ray machine for the detector D-I. The solid curve represents the polynomial regression and the frame to the right of the curve shows the associated parameters.

The same regression proceeding was performed to the curve of the detector D-II and the following values were obtained:

$$B = 10727.293$$
$$B_1 = -341.309$$
$$B_2 = 2.783$$

Then, the equation is

Illuminance = 10727.293 -341.309V + 2.783V²

It was not found in the literature any test with measurement of illuminance from a NaI(Tl) scintillation detector. However, it is clear that the behavior of the curves obtained was expected, since the intensity I of the generated X rays varies with the square of the applied kilovoltage [6], that is

$$I \propto kV^2.$$

The sensitivity volume of the NaI(Tl) crystal generates a light signal whose intensity is directly proportional to the X ray energy incident. Therefore, this light signal must also change in function of the kilovoltage square as it was actually observed.

3.3 Test with Americium Radioactive Source

To assess the performance of the detection system with the OF cable as remote probe, a test using a radioactive source of ^{241}Am was performed and the spectrum obtained was compared with that obtained with the conventional system. The two systems used different scintillation crystals with different sensitivity volumes. The electronic part, mutual for both systems, is composed by high voltage source, preamplifier, amplifier, computer, and GENIUS 2000 software for data acquisition. In each case, background (BG) spectrum was obtained before the measuring with the radioactive source.

In the conventional system, a time of 180 s was enough to generate the Americium peak as it can be verified in the Fig. 10 at the left side. Moreover, the BG signal was very low. For the system with the OF, it was necessary a time of 720 s to obtain the spectrum shown in the Fig. 10, at the right side. Investigations have shown that probably there is an optical coupling problem, that is, it is necessary to improve the optical connections between the conical systems with the lenses and the crystal and the PM tube. However, it is possible to verify that the ^{241}Am peak in the system with the OF cable is present. The ^{241}Am presents gamma decay with energy of about 60 keV. As the number of the channel is directly calibrated to show the radiation energy in keV, it is possible to verify in both systems such peak. Therefore, the conclusion is that the detection system with OF cable works as expected needing some more improvements.

4. Conclusions

Optical fiber cables are making possible the development of a range of spectroscopic probes for in situ analysis including nondestructive tests. In this way, this work presented an innovative system using an optical fiber cable to transmit the electromagnetic signal generated in a NaI(Tl) radiation detector up to the PM tube. The first tests demonstrated that the optical fiber is capable to transmit adequately the light produced in the scintillation detector by the action of an incident radiation in its sensitivity volume, as it was confirmed by the test with the X ray. Moreover, the test with the ^{241}Am source demonstrated that the system with the OF cable reproduces the gamma peak of about 60 keV in spite of the system needs

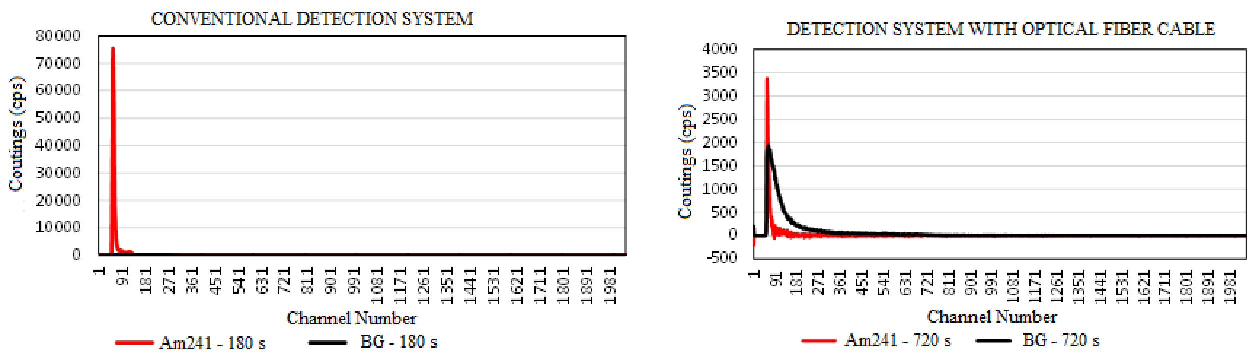

Fig. 10 Spectrum of the ^{241}Am showing, in both detection systems, the source decay peak.

adjustments. The results presented stimulate the continuity of the researches. Investigations about optical coupling in the connections with the crystal and the PM tube must be performed. When such details will be verified and the system improved, the tests using EDXRF technique will be performed.

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References

[1] Gaensbauer, N., Wrable-Rose, M., Nieves-Colón, G., Hidalgo-Santiago, M., Ramírez, M., Ortiz, W., Pacheco-Londoño, L. C., and Hernandez-Rivera, S. P. 2012. “Applications of Optical Fibers to Spectroscopy: Detection of High Explosives and Other Threat Chemicals.” In *Selected Topics on Optical Fiber Technology*, edited by Dr. Moh. Yasin, In Tech.

[2] Pitarch, A., and Queralt, I. 2010 “Energy Dispersive X-ray Fluorescence Analysis of Ancient Coins: The Case of Greek Silver Drachmae from the Emporion Site in Spain.” *Nuclear Instruments and Methods in Physics Research B* 268: 1682-5.

[3] Manso, M., Reis, M. A., Candeias, J., and Carvalho, M. L. 2013. “Portable Energy Dispersive X-ray Fluorescence Spectrometry and PIXE for Elemental Quantification of Historical Paper Documents.” *Nuclear Instruments and Methods in Physics Research B* 298: 66-9.

[4] Ardid, M., Ferrero, J. L., Juanes, D., Roldán, C., Crespo, M., Pernett, M. E., Marzal, M., Burke, et al. 2003. “Identification of Forged Works of Art by Portable EDXRF Spectrometry.” *International Centre for Diffraction Data 2003, Advances in X-ray Analysis* 46: 375-80.

[5] Knoll, G. F. 1989. “Radiation Detection and Measurement”, 2ª ed., USA, John Wiley & Sons Press.

[6] Meredith, W. J., and Massey, J. B. 1968. *Fundamental Physics of Radiology*. John Wright & Sons LTda, Great Britain.

[7] Junior, F. A. B., Costa, A. L., and Oliveira, A. H. 2014. “Proposal of Optical Fiber Use in a Portable Spectrometer.” *Journal of Multidisciplinary Engineering Science and Technology*1 (3): 31-3.