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OPTICAL DIAGNOSTIC TECHNIQUES FOR ESTIMATING GAMMA RADIATION ENERGY USING OPTICAL DENSITOMETRY

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Abstract. The main objective of this work is to investigate the changes in optical glass properties when there are exposed to gamma rays, by using different optical diagnosis techniques. The changes due to the colour centres and other defects induced in borosilicate glass by gamma rays were investigated. Four glass samples have been irradiated to about 5 MeV energy gamma rays, produced indirectly by IFIN-HH particles accelerator. The ^{12}C (p, γ) $^{12}C^*$ resonant nuclear reaction was involved in the experiment. The four samples where shielded by 0.5 mm, 1 mm, 1.5 mm, respectively 2 mm thickness of lead, each one resulting in a different darkening density. By inserting the four experimental values into the light absorption by thickness variation relation, the mass absorption coefficient of the absorbent filter can be obtained. Knowing this value and lead simulated absorption curve equation, the energy of the involved nuclear reaction can be obtained. The same method can be used for determining Compton electrons cross sections in lead.

Key words: Gamma rays energy, resonant nuclear reaction, optical densitometry.

1. INTRODUCTION

Some experiments require high energy gamma radiation sources, higher than usual ^{60}Co (1.25 MeV average energy) or ^{192}Ir (0.33 MeV average energy). These kinds of radiation can be produced by nuclear reactions in particle accelerators [1]. The interaction of the protons with a ^{12}C cylindrical target will produce resonant gamma radiation energies from tens of keV to about 5 MeV [2, 3]. The magnitude of produced gamma rays energy depends on the intensity of the used proton beam ($\approx$10 μA, 10^{15} protons s^{-1}), their associated energy (18 MeV) and the composition (graphite) and physical state (solid) of the target. Gamma rays beam can be characterized in geometric term (beam diameter and its placement due to the direction of the beam which it produces) and energy term. These characterizations were necessary as a preliminary experiment, for determining the exact position of the

proton beam and the maximum possible surface of the irradiated samples. The detectors used in gamma ray beam characterization had 100×60 mm^2 surface and 1 mm thickness borosilicate windows [4–8]. Graphite target had a 35 mm diameter, an 8 mm thickness and required 2 atm pressure water cooling. Protons beam had a 60 mm^2 ellipsoid area, 1.73 mm graphite penetration depth and a linear energy loss through electronic collisions (inelastic) of 5.8 MeV mm^{-1} while the atomic interactions (elastic) were negligible (10^{-3} MeV mm^{-1}) [9]. In the case of inelastic interactions (predominant) part of the energy and momentum incident particles is transferred to target atom, causing its superior excitation or ionization. In elastic interactions (minority), the transfer of energy and momentum of the incident particle to the target atom is not involving changing its electronic configuration. Irradiation times were a multiple of 5 h, with a load of 0.18 cumulative Coulombs on the sample.

2. EXPERIMENTAL SET-UP

From the experimental point of view, there were some things that had to be taken into account:

– cooling the target;

– using a special frame for the target;

– replacement of classical gamma rays detectors with our nonconventional glass based gamma rays detection system (avoids activation and eliminates dead time correction of classical detectors);

– ^{12}C target had about 1% of ^{13}C too, which in interaction with proton beam forming neutrons that must be stopped in a confined space, avoiding activating the experimental set-up;

– gamma beam direction was predominantly at about 45^o down related to the direction of the protons beam over any other angular distribution, these secondary directions being highlighted as well by placing large area glass based sensors around the reaction chamber.

The importance of cooling the graphite target results from the following reasons. Based on initial power calculus [10]:

$$P_i = E[\text{MeV}] \times I[\mu\text{A}] = 180 \text{ W},$$

we determined the temperature difference (ΔT), produced by radiation:

$$\Delta T = \frac{P_i \times d}{S \times k} = 343.7 \text{ K},$$

where: S – beam area (0.6 cm^2); d – protons beam penetration depth in the target (0.173 cm); k – linear coefficient of power transfer in target (0.151 Wcm^{-1}K^{-1}).

From ΔT value, noncooled target temperature is obtained: $T = 636.85$ K.

The used method takes into consideration the estimation of gamma-ray beam intensity after passing lead absorbers (0.05 cm, 0.1 cm, 0.15 cm and 0.2 cm) by measuring the darkening optical density of the glass indicators. To estimate gamma rays masic absorption, we used the absorption law (Lambert-Beer), rewritten as:

$$\ln(I(x)) = \ln I_0 - \mu_a \times x \tag{1}$$

shown in Fig. 1, where: $I(x)$ – intensity after x cm thickness; I_0 – initial intensity; $x = (\rho \times d)$ – thickness [g · cm^{-2}]; ρ – density; d – thickness [cm]; $\mu_a = \frac{\mu}{\rho}$ – mass absorption coefficient; μ – linear absorption coefficient.

Given the proportionality relation between the numbers of colour centres formed in irradiated glass, the intensity of a gamma beam which crosses it and the measured optical density, relation (1) becomes:

$$\ln(D) = \ln D_0 - \mu_a \times x, \tag{2}$$

where D is the optical density.

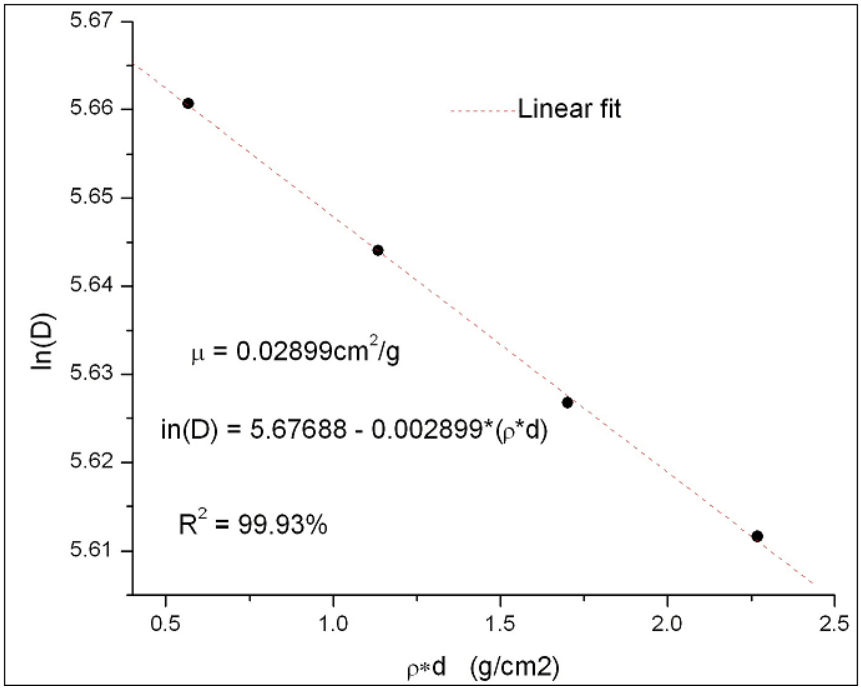

Fig. 1 – Experimental $\ln(D)$ variation as a function of absorber thickness.

3. RESULTS AND DISCUSSIONS

By identifying relation (2) to experimental data fitting, the relation $\ln(D) = 5.6769 - 0.0029 \times x$, determine the mass absorption coefficient $\mu_a = 0.0029$ cm^{2}g^{-1}. Knowing this value and considering Fig. 2, we can estimate the energy of the initial gamma radiation, *i.e.* $E\gamma$ = 4.5 MeV. The graph in Fig. 2 was obtained using XCOM software developed by NIST – Gamma photons energies database [11].

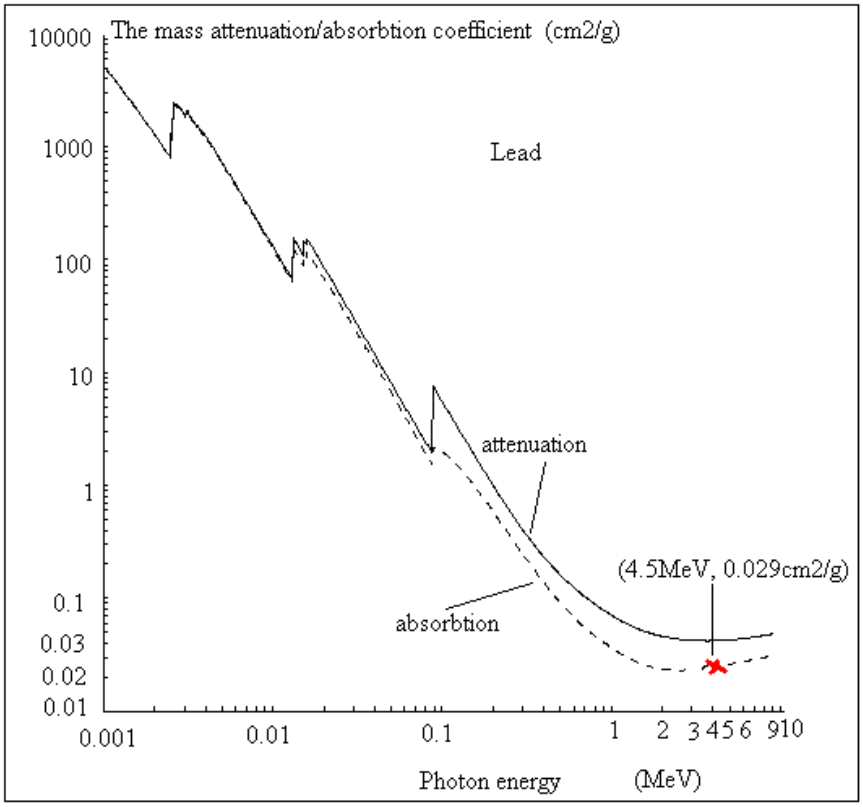

Fig. 2 – Attenuation/absorption coefficient as a function of energy.

To determine the optical density of the glass used as a detector of gamma radiation, we used a type 25-LHP-151-230 He-Ne laser (λ = 633 nm), Melles Griot, a PowerMax-USB UV-VIS power-meter and the relation:

$$D = \frac{P - P_0}{P_0}, \tag{3}$$

approximating Lambert-Beer Law: $P = P_0 \exp(-D) \approx P_0(1-D)$ for $D << 1$ [12–14].

Additionally to the relation (2), taking into account mass absorption coefficient measuring unit [$cm^2\ g^{-1}$] we can estimate Compton electrons cross section per absorbent mass unit (in our case lead). The mass absorption coefficient can be written in terms of cross section, σ in cm^2:

$$\ln(D) = \ln(D_0) - \frac{N_A \times \sigma}{A \times \rho} \rho \times d = \ln(D_0) - \frac{N_A \times \sigma}{A \times \rho} \times x, \tag{4}$$

where: N_A – Avogadro number ($6.023 \times 10^{23}\ mol^{-1}$); A – atomic mass of absorbent (207 u); p – absorber density (11.34 g cm^{-3}); e – absorber thickness (0.5 mm; 1 mm; 1.5 mm; 2 mm); σ – cross section [1 bn = $10^{-24}\ cm^2$].

From equation (4), after fitting the experimental data with a first degree curve, we obtained slope (p), used to estimate Compton electrons cross section in lead:

$$\sigma = \frac{p \times A}{N_A \times e}. \tag{5}$$

For the determination of the (p, γ) type reaction cross section and mass absorption coefficient it was necessary to determine the intensity of the gamma radiation emitted, by indirect method. Gamma rays are emitted in all directions (most of them on the same direction as the protons accelerated beam) and it is difficult to be measured in 4π. For this reason, proper placement of the four glass surfaces was as the sides of a square circumscribing the reaction chamber. In our experiment we analyzed only the predominant emission direction, which is the most important one in experiments. The gamma beam has a diameter of about 30 mm.

4. CONCLUSIONS

In this paper we estimated main energy of gamma radiation produced by a nuclear resonance reaction on light nuclei (carbon) with charged particles (protons), using a type TR19 cyclotron accelerator and a set of glasses used as radiation detectors. Estimated value (4.5 MeV) was consistent with the calculated one (4.44 MeV), in the frame of 1.33% relative difference.

This good result was achieved by measuring optical density (at 633 nm), (3), of glasses that could be used in future as detectors of high-energy gamma radiation. Unwanted neutrons activation of classical gamma rays detectors associated with this type of nuclear reactions and dead time corrections of pulses counting by conventional methods have been avoided.

The area in which the induced colour centres occurs mostly, determined on a glass sample, shows us the size and position of the beam. The optical density can be associated with a certain gamma rays dose. After the first irradiation test, using the previous method, we manage to correctly place the samples on the gamma rays beam trajectory. The gamma rays beam was found on about 45^{o} related to the accelerated protons beam.

The glass sensors placed around the circumference of the reaction chamber were not significant irradiated.

By thermal resetting of gamma rays induced optical density, these detectors can be reused, and the economic benefit of their use must be taken into account.

The irradiated samples (laser mirrors, BK7, ZF7, quartz glass) were affected by gamma radiation (occurring specific colour centres) and their optical transparency loss which can be further measured for other studies.

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