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5 February 1964

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NUCLEAR INSTRUMENTS AND METHODS 30 (1964) 209–212; © NORTH-HOLLAND PUBLISHING CO.

PULSE HEIGHT DISTRIBUTION OF ELECTRONS INCIDENT ON PLASTIC SCINTILLATORS

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Received 5 February 1964

The pulse height distribution of mono-energetic electrons (0.4 to 1.4 MeV) incident on 0.10 to 0.40 cm thick plastic scintillators is studied using a P^{32} source and a double-focusing 120° spectrometer. In some cases, two peaks can be observed, the place and height of which depends on the electron energy and the thickness of the scintillator. A theoretical interpretation of this behaviour is given and compared with experiment. The agreement is good.

1. Introduction

When plastic scintillators are used for the detection of electrons or positrons, the thickness t of the phosphor is usually chosen so that $t > R(T)$, where R is the range and T the kinetic energy of the considered particles. Sometimes very thin plastics are used, e.g. in front of a thick one in order to reduce background by counting the coincidences between the small pulses in the first and the nearly full pulses in the second scintillator.

In an experiment with energy analysed positrons, created by bombarding foils with electrons, we reduced the volume of the used scintillator considerably in order to minimize the gamma-ray background. The plastic did not stop the positrons completely but could not be considered as a very thin one either. As we needed a pulse height distribution in order to be sure that we detected only the positrons we wanted to detect, we took a differential discrimination curve. The result showed clearly two well separated peaks. Variation of the energy of the detected positrons resulted in a variation of the intensity and the place of the peaks. We have studied this phenomenon in some more detail. We have used electrons of different energies with plastics of different thicknesses and have measured each time the differential discrimination curve. The observed effects are explained and a theoretical interpretation is given.

2. Experimental set-up and results

In order to obtain rather mono-energetic electrons, a P^{32} beta ray source of about 5 mC was used, together with a double-focusing 120° spectrometer. The source width and the energy-defining slit were chosen as to have a momentum resolution $\Delta p/p = 0.04$, with which a reasonable counting rate was obtained between 0.300 and 1.400 MeV. The slit was in fact a 1.3 cm long cilindrical aluminium collimator with a diameter of 0.90 cm. The plastic scintillators (type NE 102 of Nuclear Enterprise Ltd.) were cilinders with a diameter of 3.60 cm and thicknesses t of 0.10 cm, 0.15 cm, 0.20 cm and 0.40 cm respectively. A very thin layer of aluminium was evaporated on the side of the scintillators turned towards the incoming beta-rays. A lucite light pipe, the side walls of which were covered with white paint, was mounted on the scintillator to bring the light to the surface of an EMI 6097 B photomultiplier tube. The output-pulses were amplified and counted after differential discrimination.

Figure 1 shows some of the obtained pulse height distributions for different electron energies and for different thicknesses of the scintillators. The points are normalized as to give the number of counts per MeV for one incoming electron. The indicated errors are standard deviations determined from counting statistics.

Figures 1a to 1e give the results for $t = 0.10$ cm and for $T = 400$, 450, 500, 600 and 700 keV respectively. For lower energies nothing special was seen. At 400 keV an asymmetry appears. For 450 keV a small peak can already be seen at about 250–300 keV. This peak grows with increasing electron energy and stays almost at the same place. In the same time the original peak decreases while it is going to higher pulse heights.

The points of figure 2 show the pulse height at which the peaks are observed in the 0.10 scintillator, as a function of the energy of the incoming electron. The points corresponding to the high energy peaks are situated on a straight line through the origin.

The same results were observed for other values of t. As can be seen from figures 1f and 1g the observed effects occur at higher electron energies when t is increased. Comparing figures 1e, 1f and 1g which give the pulse height distributions for 700 keV electrons in scintillators of 0.10, 0.15 and 0.20 cm respectively, one sees that the high energy peaks stays at the same place and is growing with thickness while the low energy one decreases and moves towards higher pulse heights.

* Work supported by the Belgian Interuniversity Institute of Nuclear Sciences, Brussels.

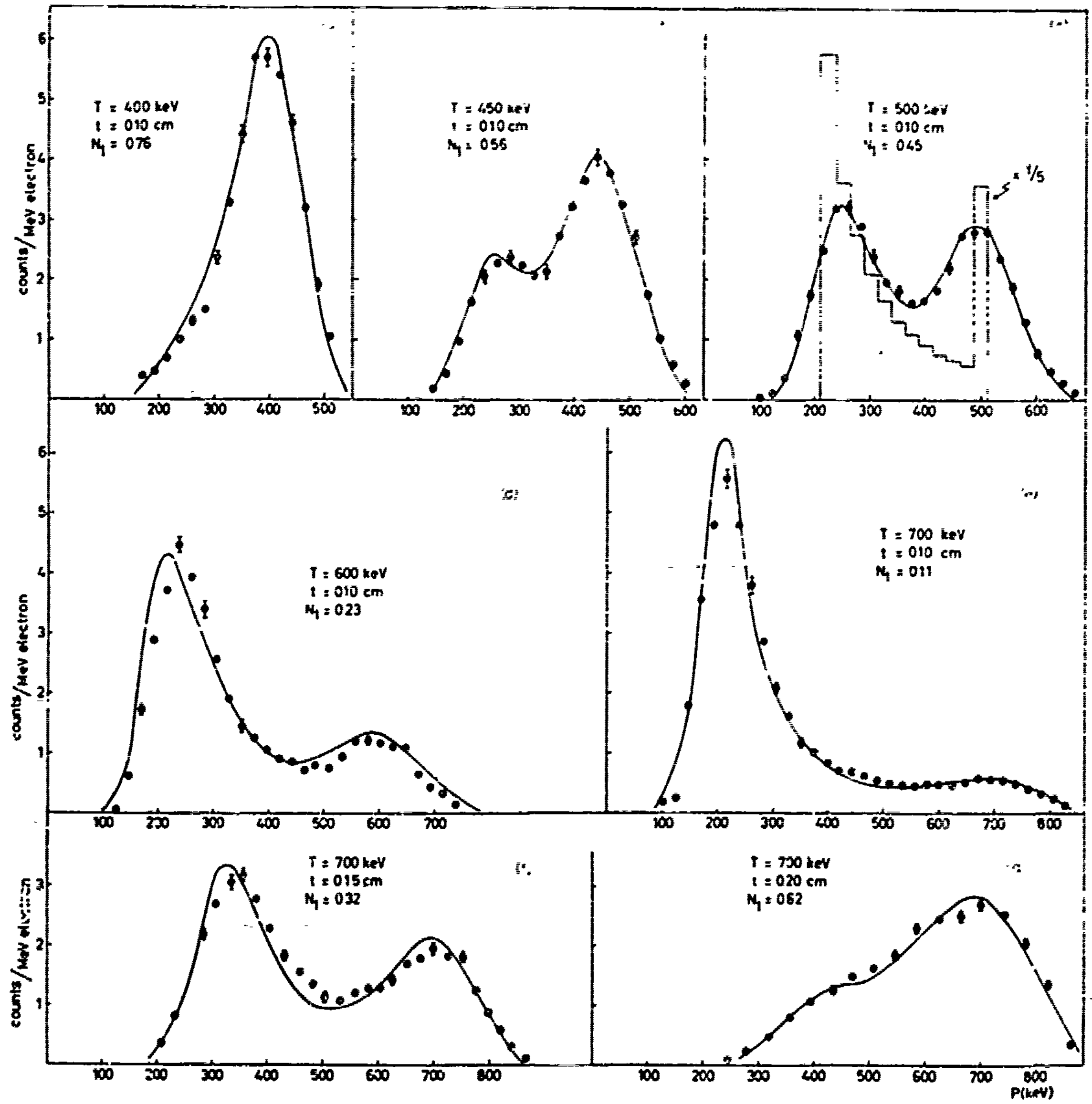

Fig. 1. Pulse height distribution of electrons of energy T, incident on a plastic scintillator of thickness t.
Points: experimental result; curve: theoretical result.
The histogram in c) gives the theoretical result before taking into account the resolution of the scintillator.

3. Interpretation of the results

We will try to explain the general behaviour of the observed results. We are not aiming at an exact theory; we just want to understand why two peaks can occur and how the place and the heights of the peaks depend on the kinetic energy T of the incoming electrons and on the thickness t of the phosphor. So we allow ourselves to make some rough assumptions.

The explanation of the observed results starts from the fact that the pulse height distribution is the consequence of the distribution of the path-lenghts of the electrons in the plastic. The pulse height P is proportional to the energy-loss resulting from ionisation and excitation. For a plastic scintillator and at the considered electron energies, radiation losses are very small and can be neglected. We now suppose [1] that the energy-loss is proportional to the pathlenght of the electron in the scintillator. Furthermore we suppose [2] that the paths of the electrons are straight lines starting from the point A where they strike the plastic (fig. 3).

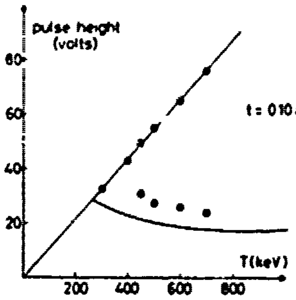

Fig. 2. Pulse height at which the peaks in the pulse height distribution occur. Points: experimental result; Curves: theoretical result not taking into account the resolution of the scintillator.

Assumptions [1] and [2] separately are rather far from reality. For [1] it is because of the fact that the energy-loss $-\mathrm{d}E/\mathrm{d}x$ is not a constant when considered as a function of T, and for [2] it is very obvious. The two assumptions together become, however, much more realistic if x is measured along the path postulated in [2] and not along the direction of the incoming electron, as is done usually.

We chose an angular distribution of the form

$$f(\theta)\mathrm{d}\theta = C\exp[-(\theta/\theta_0)^2]. \qquad (1)$$

Normalizing $f(\theta)$ by writing $2\pi\int_0^\infty f(\theta)\theta\mathrm{d}\theta = 1$, we find $C=(\pi\theta_0^2)^{-1}$.

Each electron with kinetic energy T and range R will be stopped completely in the scintillator of thickness t, if $\cos\theta \leq t/R$. By range we mean here the thickness where the absorption curve of mono-energetic electrons runs into the background and not the so called practical range R_p which is the point where the extrapolated linear portion of the curve meets the background.

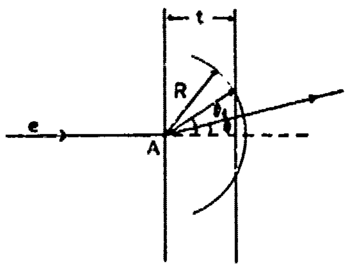

Fig. 3. Schematic drawing illustrating the assumptions made in the theoretical description.

It is clear that θ_0 must depend on T and t, but although we know that θ_0 has to increase with t and decrease with T, we will consider θ_0 as a parameter.

Let us first calculate the number of electrons staying in the plastic and giving rise to the pulse height P_1 corresponding to the full energy of the incoming electron. This number is

$$N_1(P_1) = 1-(\pi\theta_0^2)^{-1}\int_0^{\theta_1}\exp[-(\theta/\theta_0)^2]\,2\pi\theta\,\mathrm{d}\theta = \\ = \exp[-(\theta_1/\theta_0)^2].$$

in which θ_1 is defined by $\cos\theta_1 = t/R$. So we will have per incoming electron,

$$N_1(P_1) = \exp\left[-\frac{\arccos^2(t/R)}{\theta_0^2}\right] \qquad (2)$$

electrons with full pulse height P_1.

We now calculate the pulse height distribution of the electrons going through the plastic. The number of electrons leaving the phosphor under an angle between θ and $\theta+\mathrm{d}\theta$ is given by

$$N(\theta)\mathrm{d}\theta = 2\theta_0^{-2}\exp[-(\theta/\theta_0)^2]\sin\theta\,\mathrm{d}\theta \qquad \theta<\theta_1.$$

We have for the pulse height P_2 of the considered electrons $P_2 = -(\mathrm{d}T/\mathrm{d}x)\cdot(t/\cos\theta)$, where x is measured along the path. According to our suppositions we have $-\mathrm{d}T/\mathrm{d}x = T/R$, so that $P_2 = Tt/R\cos\theta$ and $\sin\theta\mathrm{d}\theta = (Tt/RP_2^2)\mathrm{d}P_2$.

Calling $N_2(P_2)$ the number of electrons per MeV and per incoming electron, giving rise to a pulse height P_2, we have for $tT/R < P_2 < P_1$

$$N_2(P_2)\mathrm{d}P_2 = (2Tt/RP_2^2\theta_0^2) \\ \exp\;[-\theta_0^{-2}\cdot\arccos^2(tT/RP_2)]\mathrm{d}P_2. \quad (3)$$

This histogram of fig. 1c shows the result obtained from formulae (2) and (3) for the case $t=0.10$ cm and $T=500$ keV, taking into account the channel width used in the experiment. For R, the value 0.238 g/cm^2 was used. This figure was obtained in the following way. From absorption curves for homogeneous beta-rays in aluminium[1]) the relation $R=1.35\,R_p$ was found to be a good fit for all electron energies used. This relation was applied for styrene, the value of R_p being taken from NBS tables[2]). All other values of R used in the computation of the theoretical curves were obtained in the same way.

In order to compare with the experimental points, one has furthermore to take into account the resolution of the scintillator. The resolution to be used will depend on the energy of the electrons and will also be different from scintillator to scintillator because of e.g. the optical coupling. Therefore we have first measured the resolution in a thick phosphor as a function of T. For the analysis, we have used for each scintillator the resolution measured for that scintillator at low electron

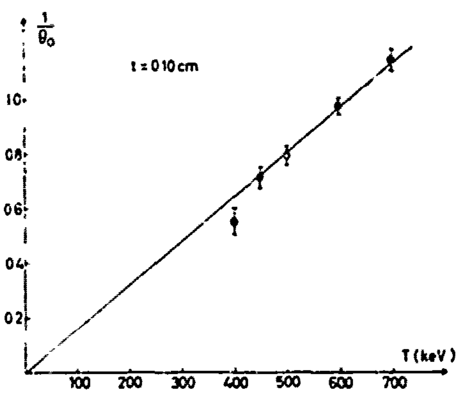

Fig. 4. Value of $1/\theta_0$ giving the best fit between theory and experiment, versus electron energy.

energies (when all the electrons are completely stopped in the plastic) and extrapolated the results to higher energies according to the energy dependance measured in the case of a thick scintillator. The final result of the analysis is shown on fig. 1a to 1g by the full curves.

As was pointed out earlier, the only parameter in the theory is θ_0. This parameter was determined for each case by trial and error. The values of θ_0 that gave the best fit were used for deriving the curves given in the figures. Fig. 4 shows the values of $1/\theta_0$ as a function of T for the case $t = 0.10$ cm. The indicated errors are rather subjective; they were determined by estimation of the extreme values of $1/\theta_0$ at which the agreement with the experimental points was not good enough. As can be seen from fig. 4, $1/\theta_0$ is proportional to T. Only the value at 400 keV comes underneath the straight line through the origin. In this case, higher values of $1/\theta_0$ could not lead to a reasonable fit. The best values of θ_0 for 700 keV electrons, for scintillator thicknesses 0.10, 0.15 and 0.20 cm are 0.86, 1.09 and 1.47 respectively. The angle θ_0 is increasing with t, but no simple relationship can be concluded from these results.

From our theoretical considerations one can easily deduct the place of the two peaks. This was done for $t = 0.10$ cm as a function of T. The result is given by the full lines on fig. 2. The full energy peak must lay on a straight line through the origin which is in fact the case. The experimental low energy peak comes at higher pulse heights than the theoretical curve indicates. This is due to the finite resolution of the phosphor as can be seen from comparison of the histogram and the full curve on fig. 1c.

In view of the good agreement between the experimental results and the theory we believe that, although the assumptions about the paths and the energy loss of the electrons in the plastic are very rough, the basic idea about the existance and the behaviour of the two peaks in the pulse height distribution is correct. It is also interesting to point out that, if one wants to stop all the electrons completely so as to have one single peak, the thickness of the scintillator has to be 1.35 times the practical range of styrene at the considered energy.

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[2] A. T. Nelms, Energy loss and range of electrons and positrons. NSB circular, 577 (1956).