Technical Papers

Pair Production and Photoelectric Effect in Scintillation Phosphors

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Scintillation counters have often been used as spectrometers to measure the energy of beta and gamma rays. The gamma ray energies have generally been determined by means of the Compton process (*1, 3–5*). The Compton recoil spectrum is generated largely within the phosphor, resulting in a continuous distribution of electron energies up to a maximum energy determined by the Compton relation $E_{max} = E_\gamma/(1+E_0/2E_\gamma)$ where E_γ is the gamma ray energy and E_0 the self-energy of an electron. The gamma ray energy is measured from the more or less sharp high energy edge of the pulse distribution. The lack of sharpness in the pulse distribution is caused by the poor distribution of pulse sizes in the photomultiplier, since different phosphors giving about the same pulse size give about the same spread in pulse size for monoenergetic radiation entering the phosphor.

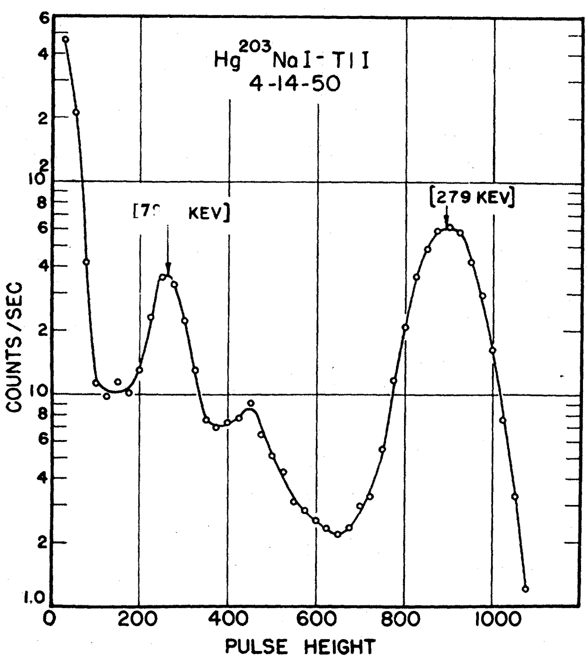

FIG. 1. Photoelectron peaks from the radiations of 51.5 day Hg^{203}.

In the organic phosphors like naphthalene, anthracene, and stilbene, the Compton process is the only interaction of importance for gamma rays from 50 kev to about 3 Mev. Below 50 kev, the photoelectric process becomes important and well-defined peaks or lines of pulses are

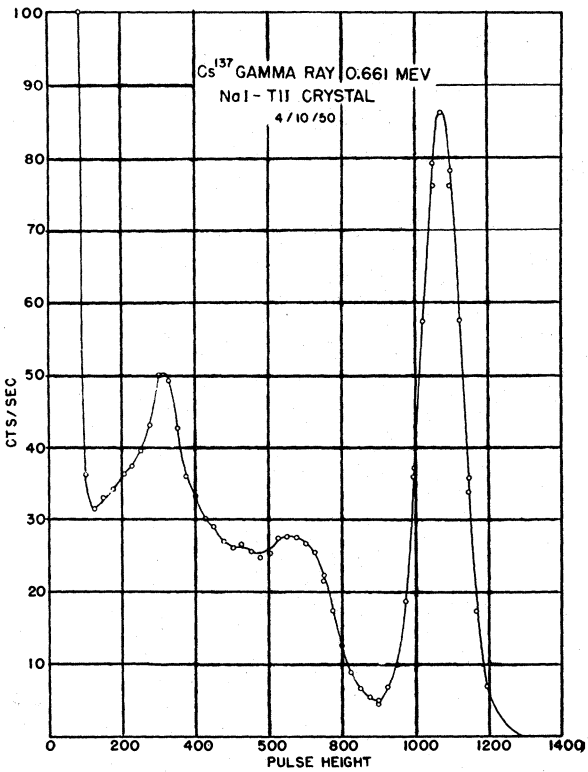

FIG. 2. Linear plot of the pulse distribution produced by 33-year Cs^{137}.

produced. Above 3 Mev, pair production peaks are seen with small intensity.

Sodium iodide activated with thallium (0.5%) is a phosphor producing large scintillation pulses of moderate decay time (0.25 μsec) and, being largely iodine, interacts with gamma rays largely by the photoelectric process from low energy up to about 1 Mev. Definite lines or peaks in the pulse distribution can be readily observed (*2*). These peaks have been observed from 25 kev to more than 4 Mev; the pulse height is very closely proportional to gamma ray energy over this whole range and energies can be determined more accurately than from the Compton electron spectrum. These peaks are not found at the gamma ray energy less the K shell binding energy of iodine, as might have been expected, but at the gamma ray energy itself, since the x-rays or Auger electrons from the excited iodine are completely absorbed and restore the whole energy of the gamma ray to the crystal. The figures show the pulse distributions produced in an RCA-5819 photomultiplier at room temperature with a NaI-TlI crystal 1.5 in. in diam and 1 in. thick. Fig. 1 is the pulse spectrum given by Hg^{203}, which has a gamma ray at 279 kev and the Hg K x-ray at 70.8 kev. The Compton electron distribution can be seen below the x-ray peak, breaking off between 450 and 600 divisions of pulse height. Fig. 2 shows the pulse distribution with a lower amplifier gain for the 0.661-Mev gamma ray of Cs^{137}. Notice that this curve, unlike the rest, is drawn to a linear scale to illustrate the resolution obtainable. The logarithmic plot is generally used, however, to allow all the details of the curve to be seen. The peak at 330 divisions (0.2 Mev) is produced by gamma rays backscattered from the lead shield. Since the source is near the crystal, these gamma rays must be within ~ 10 degrees from straight backward to reach the crystal, and hence are nearly monochromatic and near the minimum energy for a single Compton scattering (0.184 Mev). The rapid upturn below 100 divisions is due to Ba K x-rays resulting from the large internal conversion of the gamma ray.

As soon as the energy of the incident gamma rays appreciably exceeds 1 Mev, pair production within the phosphor becomes evident, producing other pulse peaks. The

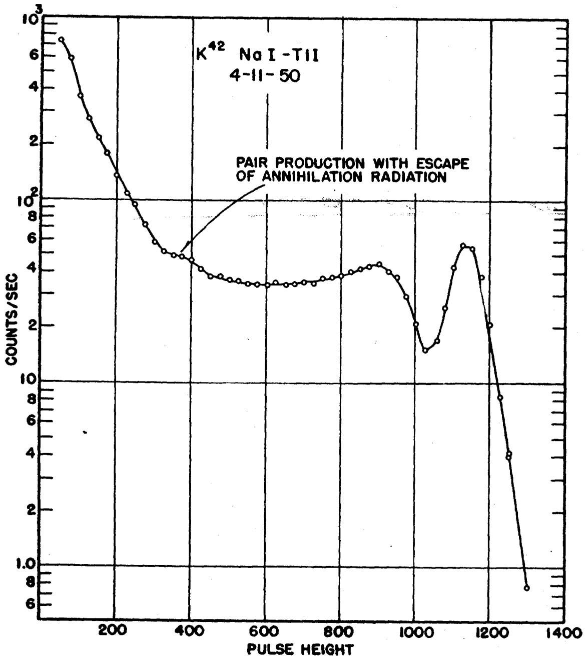

FIG. 3. Compton recoil electrons, photoelectric peak, and weak pair production peak produced by the gamma rays of K^{42}.

gamma ray of K^{42} (1.51 Mev) gives the pulse distribution shown in Fig. 3. The photoelectric peak is considerably smaller with respect to the Compton distribution than in Cs^{137} and a small peak at 385 divisions (0.51 Mev) can be seen. The measured energy difference is 1.00 Mev, which is fairly close to the 1.02-Mev difference that would be expected if this peak represented the kinetic energy of a pair produced by the gamma ray. The peak can be explained if one assumes that the two 0.511-Mev photons from the annihilation of the positron of the pair sometimes escape from the crystal without making any kind of reaction. When one or both photons are detected by the crystal a pulse is produced whose size lies between this low energy peak and the photo

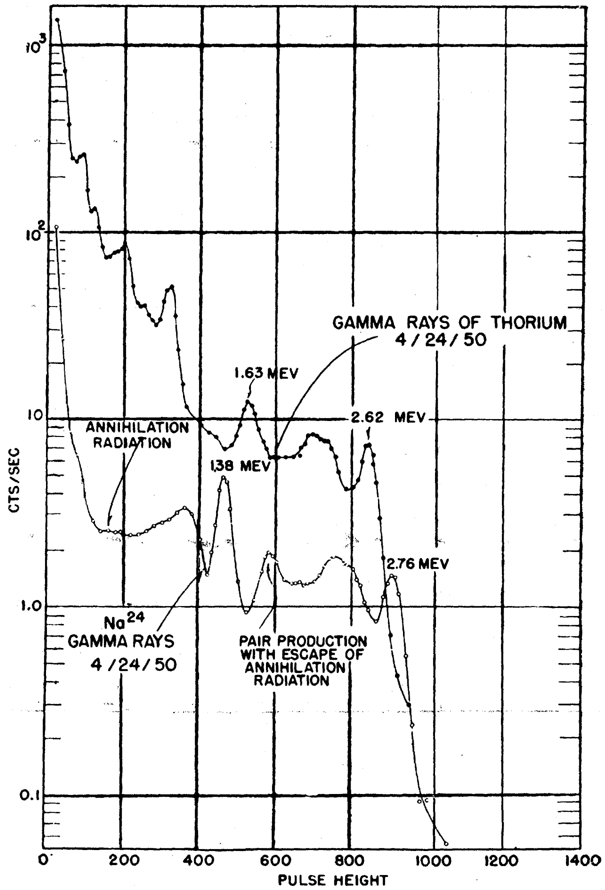

FIG. 4. Pulse distributions for the gamma rays of Na^{24} and Th in equilibrium with its products.

peak. The considerable upturn of the curve at low energies is caused by the many degenerate rays reaching the crystal, as the source was strong and at some distance from the crystal.

Fig. 4 shows the pulse distributions produced by the gamma rays of Na^{24} and thorium and its products. The 2.62-Mev gamma ray of ThC″ gives the three peaks at 2.62, 2.11, and 1.63 Mev. The upper peak is produced both by photoelectric effect with absorption of the x-ray from the iodine and by pair production where both annihilation photons are completely captured. The lower peak is pair production where both photons escaped. The region between these peaks is elevated and has a multiple peak; this seems to be due to the pair production, with capture of one photon superimposed upon the break of the Compton electron distribution. The other gamma rays from the thorium series can be seen, largely unresolved, at lower pulse heights. The two gamma rays of Na^{24} at 1.38 and 2.76 Mev, yield a complicated pattern, as shown in Fig. 4. The Compton recoil electron distribution for the lower energy gamma ray is quite distinct, but the distribution for the upper gamma ray is hidden below the pair production peaks and the broad group of pulses due to partial absorption of the annihilation photons. It cannot easily be determined what part of the peak at 2.76 Mev is due to pair production and what part is due to photoelectric effect. A rough estimate of the efficiency of the crystal for the annihilation radiation leads to a value of about half photoelectrons and half pair production. The measured energy spacing of the photo and pair peaks gives 0.99 Mev for the thorium curve and 1.00 Mev for the sodium curve. These and other similar values for the self-energy of an electron and a positron are consistently from 2% to 3% below expectation, probably due to the unsymmetrical shape of the lower pair peak. A small peak in the Na^{24} curve at about 0.51 Mev can be seen. This peak is produced by annihilation radiation escaping from the shield wall; it is produced there by the positrons of pairs due to gamma rays from the source that do not enter the crystal. This effect limits the sensitivity with which one can search for annihilation radiation in the presence of high energy gamma rays. The difficulty can be much reduced by using a shield with a liner of low Z material which is thick for annihilation radiation.

With gamma rays of about 7 Mev the lower pair production peak is the most prominent feature of the spectrum. If considerable care is used to make sure of the identity of the peaks, there seems to be no reason why this method of gamma ray measurement could not be extended to much higher energy.

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Phagocytosis during Bacteremia in Mice: A Preliminary Report

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Although the phagocytic property of the neutrophile leukocyte was known to Hayem (*13*), Panum (*22*), and Roser (*24*), it remained for Metchnikoff (*20*) and his school to emphasize the importance of this cell in normal and pathological physiology. Later investigators, including Denys and Leclef (*8*), Leishman (*18*), and Wright and Douglas (*29*), employed the neutrophile leukocyte almost exclusively in their studies on phagocytosis. That certain cells of the reticuloendothelial system also possess the same phagocytic property was clearly shown by Werigo (*28*), Levatidi (*19*), Tchistovtch (*26*), Andrews (*1*), Bull (*3–5*), Kyes (*16*), Bartlett and Ozaki (*2*), Wells (*27*), Orskov (*21*), Cappell (*6*), and Wright (*30*). Gay and Morrison (*11*) in their studies on resistance to streptococcal infections even stated that ''tissue macrophages'' are, in large part, if not entirely, responsible for the natural resistance of rabbits to experimental streptococcus infection; this in spite of the obvious presence of polymorphonuclear cells, which have so long been held entirely responsible for the cellular protective mechanism in acute infections (Metchnikoff). Recently, Taliaferro and Mulligan (*25*) in their important work on defense against malaria also advanced the opinion that resistance is: ''essentially a local immunity in strategically placed organs. Phagocytic activity, lymphoid hyperplasia, and the concomitant cytogenesis of macrophages are initiated in the spleen and are always most pronounced in this organ.''

In their studies on infections with *Plasmodium cynomolgi* in *Macaca mulatta* they observed: ''. . . an increase in the number of heterophiles (polymorphonuclears) but these cells practically never contain malarial pigment.'' The same held true in *P. knowlesi* infections.

In the following, an attempt was made to compare the phagocytic functions of the phagocytes in the peripheral blood and of those of the fixed tissues. The work was done in normal and immunized mice subjected to severe bacteremia. Phagocytosis was also determined by the traditional test tube procedure. In addition, the effects of magnesium chloride and gelatin on phagocytosis are herein reported.

Experimental work. The mice were separated into various groups, each comprising animals of similar age and sex and, as nearly as possible, also of similar weight. Prior to the induction of the bacteremia, blood was obtained for total and differential counts. Bacteremia was produced by the intravenous injection of a standardized suspension of a nonpathogenic coccus, *Micrococcus candidus*. Following the injection and at various intervals of time—30 min and 1, 2, 3, 4, 5, and 6 hr—the animals were again bled for total leukocyte and differential counts, for the determination of the percent of active neutrophile leukocytes, and for the number of cocci found per neutrophile leukocyte.

The data thus obtained were treated statistically by the method of Fisher (*9*), Fisher and Yates (*10*), or Pearl (*23*). When the number of animals was greater than 30, the method of the standard error was employed, while for series of less than 30, the Student's T test was applied.

All phagocytic and differential counts were done with complete objectivity. The slides were all recoded before they were examined microscopically.

General observations. Upon injection of the *candidus* into normal mice a drop in the total number of white blood cells occurred in the course of from one to four hours after the injection. This was observed in 49 out of a series of 62 female animals or 79.1 percent. In 22 immunized females, all showed leukopenia in the course of from one to five hours.

In animals sacrificed in the course of the leukopenia it was observed that the neutrophile leukocytes accumulated in their lungs. However, phagocytosis by the mononuclear cells in this area *preceded* the leukopenia. Large numbers of injected cocci were trapped in the lung.