The Measurement of Gamma-Ray Energies with Single Crystals of NaI(Tl)

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A new method is described for determining gamma-ray energies and intensities. The basis of the method is the observation of narrow pulse distributions (lines) in the scintillations of NaI(Tl). Due to the presence of the iodine component, pair production and the photoelectric process produce relatively sharp lines in the pulse distributions. The Compton process may also be used in determining gamma-energies. Approximate theoretical curves of the pulse distribution are shown. Experimental spectra resemble the theoretical patterns, except for differences in intensities discussed in the text. Electronic as well as photographic techniques for obtaining spectra are described. With these methods well known spectra are confirmed and new results in the case of Ga^{66} are given. With a source of less than 10^{-9} curie of K^{40} the energy of the gamma-ray has been determined to within two percent. The method described should make possible a new approach to the study of weak gamma-radioactivities and unknown gamma-ray spectra.

IN an earlier paper[1] one of the authors showed that sodium iodide, activated by a small thallium impurity, was a useful material for detecting gamma-rays in the device now called a scintillation counter. In those studies it was also shown that gamma-rays of different energies could be distinguished by their corresponding pulse size distributions. It was stated, furthermore, that the rules for distinguishing gamma-rays of different energies were not clear. Since that time much progress has been made in the solution of this problem and the main point of this paper is to report on some aspects of this new knowledge.[2] It was also demonstrated[1] that potassium iodide was a useful material, but since its pulses are smaller than those of NaI it will not be considered below.

Gamma-rays interact with matter by the three well-known processes of Compton effect, photoelectric effect, and pair production. In sodium the photoelectric and pair production processes are rather unimportant compared with the Compton effect for energies up to about 5 Mev. In iodine, on the contrary these effects are by no means negligible and in fact offer new possibilities for energy measurements with gamma-rays.

Figure 1 shows the variation of absorption coefficient[3] for the iodine constituent (85 percent by weight) of NaI. Thallium is present to less than 0.5 percent by weight and will be neglected in the approximations discussed. On the basis of these cross sections and neglecting the small contribution due to sodium,[4] the curves of Figs. 2, 3, 4 show approximations to the pulse distributions which may be expected theoretically for gamma-rays of the indicated energies. In these figures the photoelectric (*Ph*) and pair (*P*) pulse distributions have been calculated on the following assumptions. (1) All photoelectric processes result in the production of electrons in the NaI crystal with the full energy of the gamma-ray. (2) The pulse distributions are Gaussian and due entirely to the statistics of the photo-multiplier tube. (3) Approximately 1000 electrons are produced at the photo-multiplier cathode surface for a 1.0-Mev electron[5] in the crystal. (4) The pair energy is the gamma-energy minus 1.02 Mev and all pair pulses are uniform and subject to the statistical width considerations just described. The Compton distributions in the figures have been corrected only partially (in the energy regions near the high energy edges) for the broadening effects due to statistics of the photo-multiplier since these distributions are already continua and the figures are only approximations to the actual pulse distributions. The areas under the various Gaussian components have been chosen according to the data in Fig. 1. In the assumption (1) above, it is suggested that

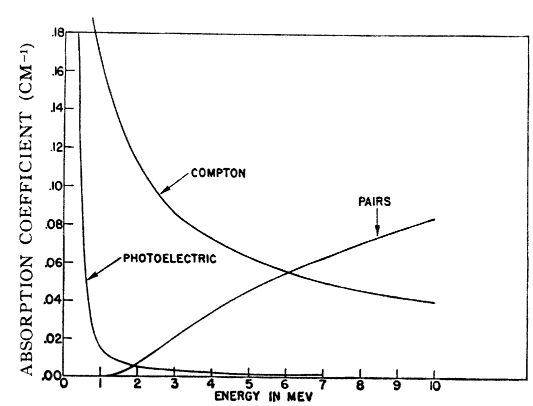

FIG. 1. The cross section for the primary processes of photoelectric capture, Compton scattering and pair production in the iodine constituent of NaI(Tl).

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† This work was partially supported by the U. S. Army Signal Corps and by the joint program of the ONR and AEC.

[1] R. Hofstadter, Phys. Rev. **75**, 796 (1949); **74**, 100 (1948).

[2] Work in some respects similar to that here reported was also done by S. A. E. Johansson, Arkiv f. Fysik **18**, 171 (1950). R. W. Pringle, K. I. Roulston, and S. Standil, Phys. Rev. **78**, 627 (1950). P. R. Bell and J. M. Cassidy, Phys. Rev. **79**, 173 (1950).

[3] R. G. Evans, *Advances in Biological and Medical Physics* (Academic Press, Inc., New York, 1948), Vol. 1, pp. 167–168.

[4] If it is desired to include the effect of sodium the Compton curve should be increased by 21 percent, the pair curve increased by four percent and the photoelectric curve should remain unaffected.

[5] J. A. McIntyre and R. Hofstadter, Phys. Rev. **78**, 617 (1950).

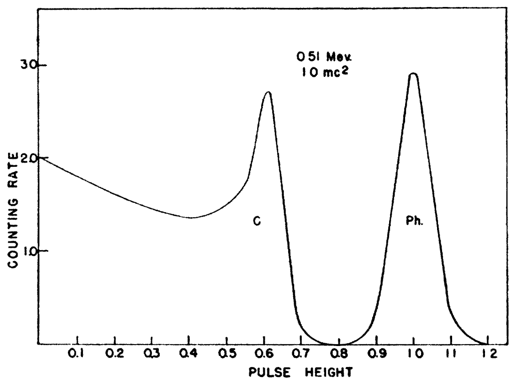

FIG. 2. Approximate pulse distribution to be expected in a NaI(Tl) single crystal when struck by 0.51-Mev gamma-radiation if only primary processes occur.

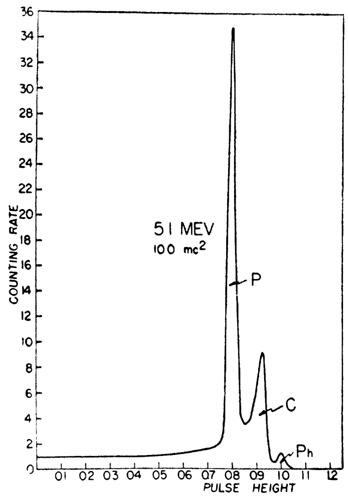

FIG. 4. Approximate pulse distribution to be expected in a NaI(Tl) single crystal when struck by 5.1-Mev gamma-radiation if only primary processes occur.

the energy is the full energy of the gamma-ray and *not* that energy minus the binding energy of a K, L, etc. electron. For if a K, L electron is set free the subsequent x-ray produced will also be captured, perhaps after degradation, so that eventually electrons are produced with all the energy of the x-ray.

Assumption (3) indicates a figure, 1000 electrons/Mev, which differs by a factor of two from a previous estimate.[5] The difference arises from (a) inclusion in this estimate of the statistical widening of the pulses due to variable multiplication at the dynodes of the multiplier and (b) use in this estimate of the standard deviation in place of the half-width at half maximum used earlier, by mistake. The number of electrons N corresponding to a peak of standard deviation σ and mean value V is

$$N=[r/(r-1)](V/\sigma)^2,$$

where r is the mean value of the multiplication factor at the dynodes. r is assumed to be 4 for this calculation.

We have found experimental evidence for the reality of the curves of Figs. 2, 3, 4. Furthermore, this evidence opens up an entirely new and most powerful method of investigating the energies and intensities of gamma-rays. An example discussed below (K^{40}) shows that sources as weak as 0.001 microcurie can be investigated successfully so that the gamma-ray energy can be found to within two percent or better.

Figure 5 shows the experimentally observed pulse distribution in Au^{198} which has principally a gamma-ray line at 0.411 Mev. The curve shown was taken with a differential discriminator,[5] an EMI photo-multiplier tube (35 μa/lumen) and a 0.5-in. crystal cube of NaI,

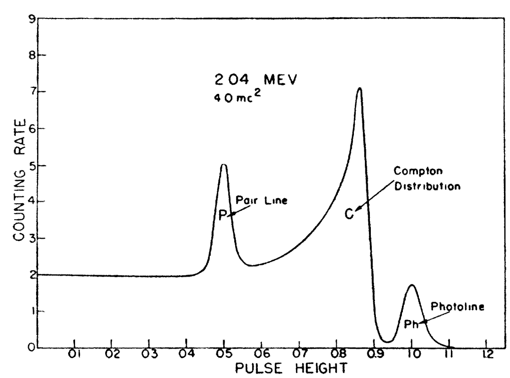

FIG. 3. Approximate pulse distribution to be expected in a NaI(Tl) single crystal when struck by 2.04-Mev gamma-radiation if only primary processes occur.

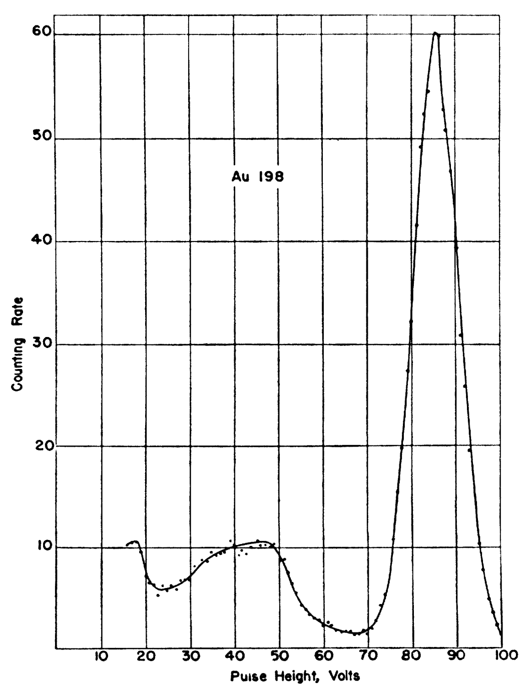

FIG. 5. Experimental discriminator pulse distribution observed with Au^{198} 0.411-Mev gamma-radiation. Data have been taken with a single channel discriminator. The photo-peak at 85.5 volts is quite accurately Gaussian. To obtain counts per second multiply ordinate scale by 1.06.

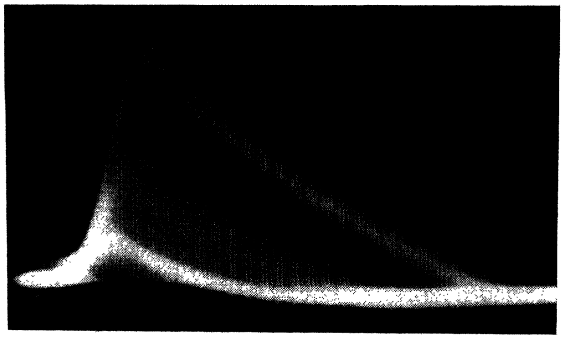

FIG. 6. The pulse distribution for Au^{198} photographed on an oscilloscope screen. The bright band at the top is the photo-peak at 0.411 Mev. Below the gap lies the Compton distribution, with a relatively sharp edge. Superposed on the Compton distribution is a low energy gamma-ray at 0.075 Mev.

in a collimated arrangement of the gamma-rays in which the beam struck the middle third of the crystal and had about a 1° angular width. For this energy the curve taken without collimation is very similar. The peak at 85.5 volts is due to the photoelectric effect and also to gamma-rays scattered by the Compton process whose second-scattered (third, etc.) gamma-rays are finally completely captured by the crystal. The broad distribution peaking near 48 volts is due to the Compton effect as a primary process, the scattered gamma-ray escaping the crystal. Also indicated near 19 volts is partial evidence of another peak. Figure 6 shows the pulse distribution for Au^{198} as photographed on an oscilloscope screen. One sees clearly the "photoelectric" line at the top, the broad Compton distribution and the low energy peak corresponding to the flattening near 19 volts in Fig. 5. The low energy peak corresponds to an energy of about 0.075 ± 0.006 Mev.

This line has not been reported in the literature[6] although its low energy may have made its detection difficult. An x-ray line of mercury following internal conversion of the 0.411-Mev line is a possibility. A similar K x-ray line has been observed recently by Hill[7] in Au^{199}. On the other hand, since only rough chemical separation has been employed, an impurity might be the source of this line. Other structure in this spectrum will be discussed below.

Figures 5 and 6 show a strong resemblance to Fig. 2 when the proper correction is made for cross sections at the energy 0.411 Mev. At 0.411 Mev the areas under the Compton curve and under the photoelectric peak should be approximately equal if only primary processes occur. Nevertheless the area under the "photoelectric" peak is too large to be given by this simple theory. This fact has led us to suggest[5] that secondary processes contribute to the photoelectric peak.

The photo-line of Fig. 5 has been fitted empirically by a Gaussian curve. The fit is excellent and within the experimental error at every point above a counting rate of 5, in the ordinate units of Fig. 5. The half-width, assuming only statistical causes of broadening, results in an assignment of about 400 electrons at the photocathode for the energy 0.411 Mev. This value is in agreement with the figure 1000 electrons/Mev obtained previously from the Co^{60} lines and a different crystal.

Au^{198}, because of the low energy of the gamma-ray, offers no evidence of pair production. The second case to be discussed, Na^{24}, does indeed show a pair line. Na^{24} has two gamma-rays of energy 1.38 Mev, 2.76 Mev. The pulse distribution taken with the differential discriminator has been published recently.[8] Figure 7 shows the pulse distribution photographed on the oscilloscope screen. At the top the weak photoelectric line (2.76 Mev) appears. Under it one can see the broader, more intense Compton distribution due to the 2.76-Mev line. Below it is the strong pair line at 1.74 Mev. Below the pair line lie the 1.38-Mev photo-line and the Compton distribution of the 1.38-Mev line. Between the pair line (1.74 Mev) and the Compton distribution of 2.76 Mev there is a weak band easily observed in the original plate. This band appears in the position to be expected if either of the gamma-rays produced on annihilation of the pair-produced positron is captured in the crystal. Figure 2 of an earlier publication[8] also shows this band. With a larger crystal this band will undoubtedly become more prominent, because of increased capture of annihilation radiation.

It may be observed that the Compton peaks have a characteristic shape (Fig. 2 of reference 8); they are sharp on the high energy side and show a gradual falling off on the low energy side. This feature will be of help in analyzing unknown spectra.

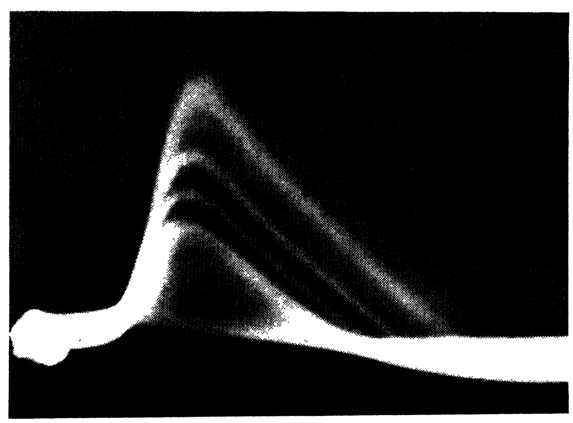

FIG. 7. The pulse distribution for Na^{24} photographed on an oscilloscope screen. The weak 2.76-Mev photo-peak appears at the top. Below it lies the Compton distribution and the prominent pair peak of the 2.76-Mev radiation. Between the pair peak and the Compton edge lies a weak band due to capture of annihilation radiation in the crystal. The photo-peak of 1.38 Mev lies above the continuum due to the Compton effect for 1.38 Mev.

[6] A. C. G. Mitchell, Rev. Mod. Phys. **22**, 36 (1950).
[7] R. D. Hill, Phys. Rev. **79**, 413 (1950).
[8] R. Hofstadter and J. A. McIntyre, Phys. Rev. **79**, 389 (1950), Fig. 1.

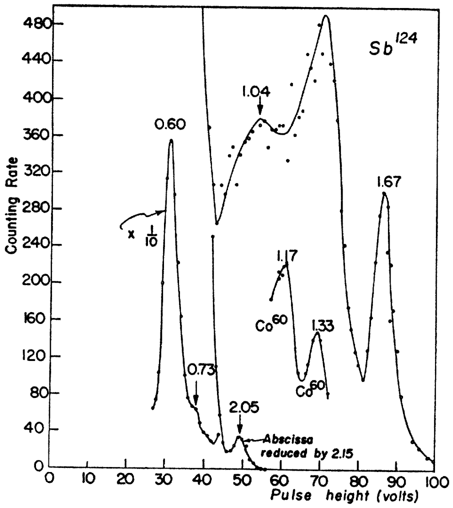

FIG. 8. The discriminator run for Sb^{124} using a collimated source. Co^{60} calibration lines are also shown.

It is clear from the figures shown that single crystal pulse distribution curves can be used to determine gamma-ray energies by locating correlated triads of peaks (*Ph*, *C*, *P*) when the energy is greater than 1.02 Mev and correlated pairs of peaks for lower energies. In fact, the interval between the pair line and photoline offers an internal calibration scheme.[9] However, it is also clear that the presence of numerous peaks due to a single line will make for troubles in analyzing a complex spectrum of gamma-rays. A larger crystal will add more bands and therefore more complexity, as evidenced in the case of the Na^{24} example. In such cases other methods[8,10] involving two or more crystals in coincidence will be useful. Perhaps an organic crystal which interacts essentially by Compton processes with the gamma-rays will also be useful as a rough indication of the more prominent gamma-ray lines.

The gamma-rays 1.38 and 2.76 Mev in Na^{24} are of equal intensity. If only primary processes occur in the gamma-ray—NaI(Tl) interactions, the ratio of intensities of the various peaks should be given by the curves of Fig. 1. Comparing the areas of Peaks II, III, and V, respectively, in Fig. 1 of the earlier paper[8] we obtain the respective relative values 1.21, 1.00, 0.48. According to the theoretical curves of Fig. 1 these ratios should be 0.64, 1.00, 0.25. As suggested in the case of Au^{198} the photo-peaks in Na^{24} also have contributions of secondary origin and are larger than the theory indicates. It is also clear that the pair peak III has lost intensity, because of absorption of annihilation radiation in the crystal, to the band between III and IV. A further small contribution to the photopeak arises from simultaneous capture of two annihilation quanta. Intensities cannot be determined therefore at first glance and corrections will be required for the secondary processes of capture. Nevertheless, rough intensities can be told at a glance. It is also probably true that the curves of Fig. 1 of this paper have not been verified completely and further work along these lines may show what corrections are needed to make them more perfect.

Figure 8 shows the more complex spectrum of Sb^{124}. The known gamma-rays[6] of Sb^{124} are located at 0.603, 0.650, 0.714, 1.71 and 2.06 Mev. Their intensities are given roughly by Kern *et al.*[11] Figure 8 shows also the Co^{60} (1.33, 1.17 Mev) photo-lines, useful in calibration of the scale. The known lines[11] are all shown, except the weak line at 0.650 Mev which is apparently concealed in the much more intense 0.603-Mev line. The unusual

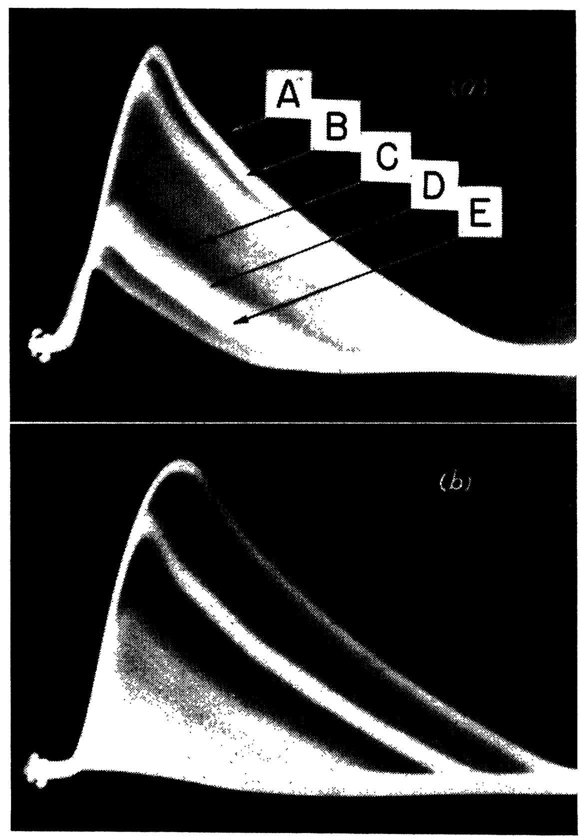

FIG. 9. (a) Photographic representation of Sb^{124}. *A* represents the weak 2.05-Mev photo-line. *B* is the 1.67 photo-line. *C* represents the weak pair line of 2.05 Mev. *D* (see also Fig. 9b) represents the weak 0.73 photo-line and *E* the strong 0.60 photo-line.

(b) Expanded photographic representation of Sb^{124} obtained by increasing the gain of the amplifier. The higher energy peaks are crowded into the topmost edge. The bright band in the middle is the 0.60-Mev photo-line and under it lies the Compton distribution for this line. Above the 0.60-Mev photo-line is the weak 0.73-Mev line observed in Fig. 9a. The unusual crowding of topmost peaks is not typical and resulted from special settings of oscilloscope amplifier gain.

[9] Let the photo-line have the position V_1 and the pairline the position V_2. The energy of the gamma-ray, E, is then

$$E=\frac{2mc^2}{\left[1-\left(\frac{V_2}{V_1}\right)\right]}$$

[10] R. Hofstadter and J. A. McIntyre, Phys. Rev. **78**, 619 (1950).

[11] Kern, Zaffarano, and Mitchell, Phys. Rev. **73**, 1142 (1949).

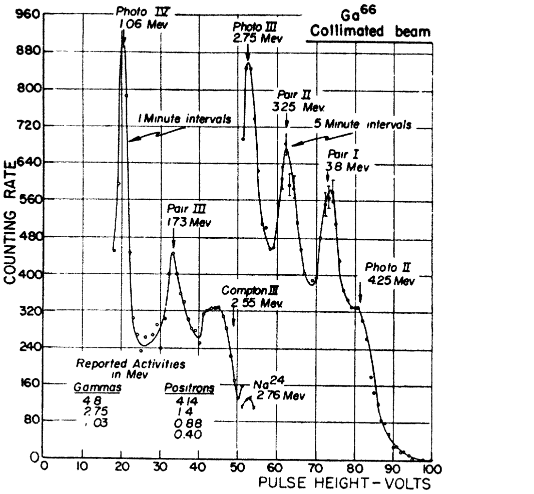

FIG. 10. Discriminator spectrum of Ga^{66}. Na^{24} photo-line is used as a reference (below). A pair line is observed at about 62 volts corresponding to a new gamma-line at 4.27 Mev.

shape of our 1.67-Mev line at higher energies is probably due to the superposition of the 2.05-Mev Compton distribution and the 1.67 photo-line. The band at 1.04 Mev is probably due to pair production of the 2.05 line. The pair peak of 1.67 Mev is weak and is concealed under the 0.603-Mev line. The differences between our observed energies and those previously reported are within our experimental error (~two percent) but this error does not represent a real measure of the possible accuracy of this method. Careful temperature control of the electronic parts is an essential element in making precise measurements of energy. In the time available we have unfortunately not been able to eliminate drifts of the discriminator and associated equipment. Our voltage control of the photo-multiplier however has been better than ± 0.1 percent.

Figures 9a and 9b show the photographed pulse distributions in Sb^{124}. The strong peak at B in Fig. 9a is the 1.67-Mev photo-line. The weak peak at A, above B, is due to the 2.05 line. At C is the pair line 1.04 Mev. D is the 0.73-Mev photo-line and E the 0.60-Mev photo-line. Figure 9b was taken with greater amplifier gain, resulting in distortion and crowding together of the higher energy lines, but shows clearly the weak 0.73 Mev above the prominent 0.603-Mev photo-line near the center of the pattern.

Another example of a complex scheme is provided by Ga^{66}. In this case we have found evidence for a new gamma-ray line near 4.30 Mev which decays with the known half-life of Ga^{66}. We are also able to estimate rough intensities of the gamma-lines in this spectrum. Figure 10 shows the spectrum observed with the differential discriminator. Figure 11 shows the lower part of the spectrum enlarged by increase of amplifier gain. The peak at 3.25 Mev is believed to represent the pair line of a new gamma ray of intensity roughly equal to that of the 4.8-Mev line.[12] Figure 12a shows the oscilloscopic representation and Fig. 12b a second representation with increased amplifier gain. A discriminator curve of the lowest region, not shown, shows peaks[13] at 0.296 Mev and 0.186 Mev. These and other curves show that the photo-line at 1.06 Mev has an area about twice that of the 2.75-Mev pair line. Referring to Fig. 1 this means that the 1.06-Mev line is about twice as intense as the 2.75-Mev line. However, as we have previously observed, the photo-peak is usually larger than expected by about a factor of two and a corrected ratio of intensities of 1:1 for these gamma-lines seems to be reasonable.[14] It is interesting, and in good agreement with Moffat and Langer's energy level scheme for Zn^{66} that our new line at 4.27 Mev fits in with the proposed level at 4.29 Mev.

Three final examples are given, the first of which relates to an important point requiring consideration when observing single crystal spectra. The latter two illustrate the power of the method. Figure 13 shows the oscilloscopic representation of Co^{60} uncollimated. In addition to showing the two photo-lines and the composite Compton peak, there is a small band located near 0.2 Mev. This does not represent a real gamma-line and does not appear in the same strength when a collimated beam is used. It is believed that this peak is due to back scattered gamma-rays, captured (mainly photoelectrically) by the NaI and produced in the surroundings of the crystal and perhaps also at crystal

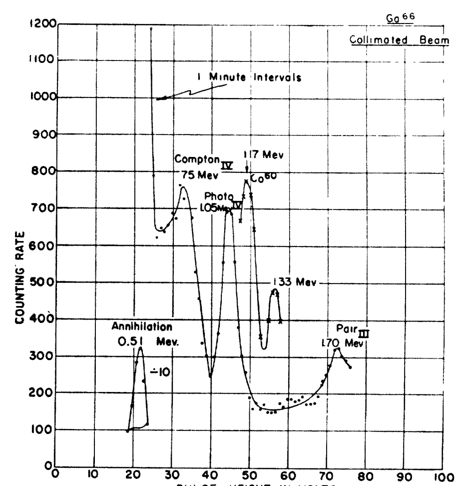

FIG. 11. Expanded discriminator run of the lower energy part of the Ga^{66} spectrum.

[12] R. D. Moffat and L. M. Langer, Phys. Rev. **79**, 237 (1950).

[13] The peaks at 0.296 and 0.186 Mev have not been followed to see whether they have the same decay period as Ga^{66}, and are quite probably due to Ga^{67} made by $(\alpha,2n)$ reaction on Cu^{65}. Ga^{67} has a half-life of 78 hours and has gamma-lines at 0.30, 0.18 and 0.093 Mev. We have not looked for the lowest energy gamma-line in our work.

[14] A private communication from Dr. L. M. Langer informs us that the ratio 300:1 reported in the abstract (reference 12) was a typographical error and the actual ratio is close to unity, as we find.

edges by Compton processes. Probably other "ghosts" due to multiple scattering will also appear.

Figure 14 shows a double exposure of the gamma-rays from a source of Au^{198}. The upper band was exposed for about 700 seconds and the lower intense band (0.411-Mev photo-line) for about 2 seconds. It therefore appears that this gold sample, made in the pile, shows another line at 0.66 Mev in addition to those at 0.411 Mev and at 0.075 Mev. Initial measurements with the differential discriminator showed that the weaker line at 0.66 Mev was present to about 1 part in 250 compared to the main line at 0.411 Mev. Subsequently the 0.66-Mev line grew stronger relative to the 0.411-Mev line. After the gold activity had decayed further, a second line at about 0.86 Mev appeared and possibly a third at a higher energy. The impurity responsible for these lines is unknown but may be Ag^{110} formed by neutron capture in Ag^{109}. Ag^{110} has strong gamma-lines at 0.66, 0.88 and 1.5 Mev.

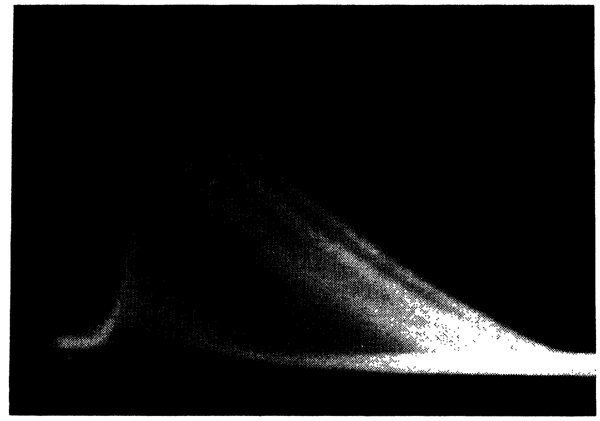

FIG. 13. Co^{60} photographic representation observed with uncollimated source. Weak band near bottom of pattern is a spurious peak produced by backscattered gamma-rays. The two photo-peaks are shown at top.

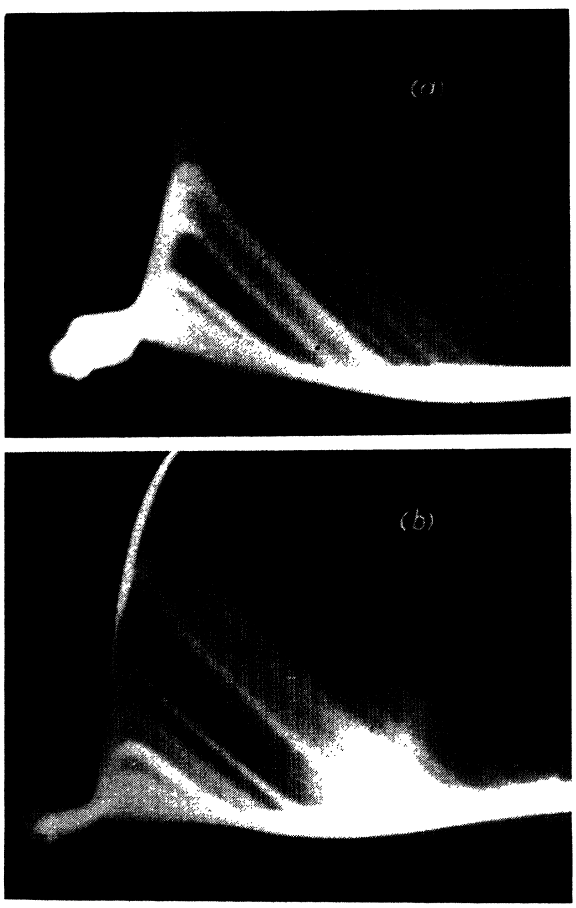

FIG. 12. (a) Photographic representation of Ga^{66}. The three higher energy peaks corresponding to Pair I, Pair II, Photo III appear at the top followed below by the broad Compton distribution of the 2.75-Mev line.

(b) Expanded photographic representation of Ga^{66} emphasizing low energy peaks. The very bright band at the bottom is the annihilation radiation photo-peak. Above it are the Compton distribution and photo-peak of the 1.05-Mev line. There is a gap leading to the 1.73-Mev pair peak which is superposed on the 2.75-Mev Compton distribution.

We have also examined the spectrum of K^{40}, using an enriched sample of this material.[15] The amount of K^{40} used was 0.6 mg and represents an effective source strength of less than 0.001 microcurie gamma-ray activity. Figure 15 shows the data observed with this source. The background was made negligible by enclosure of the detecting apparatus in a 6.0-inch wall lead house. The two peaks of Na^{24} (1.38-Mev photo-line and 1.74-Mev pair line) and the 1.33-Mev peak of Co^{60} were used for calibration. From these data the photo-line of K^{40} appears at 1.48 ± 0.02 Mev which agrees with other recent determinations[2,16] within the experimental error. Photographs of the oscilloscopic representation

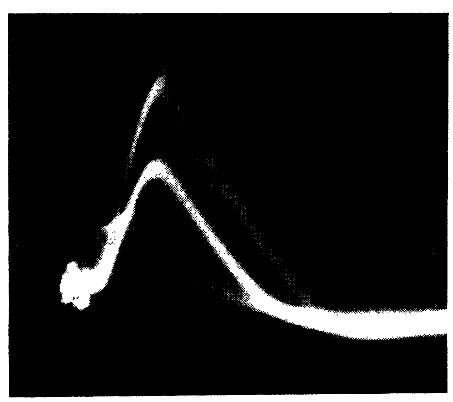

FIG. 14. Double exposure of Au^{198} gamma-rays. Peak at top is due to weak 0.66-Mev gamma-ray present initially to about one part in 250 of the strong 0.411-Mev gamma-ray whose photo-peak stands out sharply in the photograph.

[15] We are indebted to Dr. C. S. Wu (Columbia University) and the Isotopes Branch ORNL, for putting sources of enriched K^{40} at our disposal.

[16] Pringle, Standil, and Roulston, Phys. Rev. **77**, 841 (1950). P. R. Bell and J. M. Cassidy, Phys. Rev. **77**, 409 (1950).

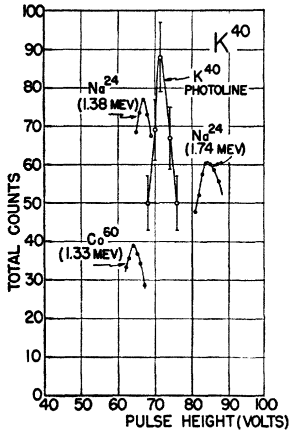

FIG. 15. The photo-line of K^{40} and Na^{24} and Co^{60} calibration lines. The source strength was less than 10^{-9} curie. The data were taken in about five hours. The K^{40} energy is 1.48 ± 0.02 Mev.

of the pulses in K^{40} show that there is no other gamma-ray present with an intensity greater than about 10 percent of the 1.48-Mev line. Our success with the photographs of oscilloscope patterns suggests that this technique will be valuable for work with weak sources since it serves the purpose of a multichannel discriminator. Densitometer traces we have made of gamma-ray patterns resemble the discriminator curves very closely. For initial spotting of gamma-ray lines this technique will probably not be surpassed.

We are greatly indebted to Drs. Dean Cowie and P. Abelson of the Carnegie Institution of Washington for supplying us with sources of Ga^{66}. We wish to thank Drs. E. P. Tomlinson and J. L. Simons for sources of Au^{198}.

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Photo-Disintegration Cross Sections of Deuterium and Beryllium for the Gamma-Rays of Sodium 24 and Gallium 72

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(Received June 22, 1950)

Photo-neutron yields from spheres of D_2O and Be containing Na^{24} and Ga^{72} gamma-ray sources were measured by spatial integration of induced foil activities in a large paraffin block. A standard neutron source was used to calibrate the apparatus.

The Ga^{72} and Na^{24} sources were subsequently dissolved, and their radioactive strengths were measured by beta-counting of aliquots. The data so obtained, when combined with the known wall thickness of the spheres led to the following results after the application of appropriate corrections:

(1) Photo-disintegration cross section of D at 2.76 Mev: 14.3×10^{-28} cm^2
(2) Photo-disintegration cross section of Be at 2.76 Mev: 6.74×10^{-28} cm^2
(3) Cross section of D at 2.50 Mev multiplied by intensity of 2.50 Mev line in quanta per Ga^{72} beta-emission: 2.81×10^{-28} cm^2
(4) Sum of cross sections of Be at 1.84, 2.20 and 2.50 Mev weighted according to respective gamma-intensities in Ga^{72}: 2.16×10^{-28} cm^2

These results are believed accurate within 8 percent. Agreement with theory is discussed for both D and Be.

I. INTRODUCTION

THE measurements to be described in this paper were made in 1945–46. At that time a rather complete survey of photo-neutron yields was envisaged. Since circumstances have prevented the completion of such a survey, we describe here our study of the yields from Na^{24} and Ga^{72}. The results may be of interest inasmuch as very little has been published on this subject. Comparable work which has come to our attention is that of Russell, Sachs, Wattenberg, and Fields[1] and Wilson, Collie, and Halban.[2]

It is easy to see from first principles that if a gamma-emitting radioactive source is placed in a small spherical cavity in the center of a sphere of beryllium or heavy water, the number of photo-neutrons emitted per second will be given by

$$S=QN(\Sigma_i\alpha_i\sigma_i) \qquad (1)$$

where Q is the number of radioactive transformations taking place per second within the source, N is the wall thickness of the spherical shell expressed in terms of the number of Be or D atoms per square centimeter, α_i is the relative intensity (i.e., the mean number of quanta per radioactive transformation) of the ith gamma-ray above the photo-neutron threshold for beryllium (1.67 Mev) or deuterium (2.235 Mev), and σ_i is the (γ, n) cross section at the energy of the ith gamma-ray. This expression will hold so long as there is negligible neutron and gamma-ray absorption in the spherical shell. We are here concerned with the experimental measurement of the $\Sigma_i\alpha_i\sigma_i$. In the case of Na^{24} this leads to a value for the photo-dissociation cross sections at 2.76 Mev,

[1] Russell, Sachs, Wattenberg, and Fields, Phys. Rev. **73**, 545 (1948).
[2] Wilson, Collie, and Halban, Nature **163**, 245 (1949), and supplementary communication from Professor Halban.

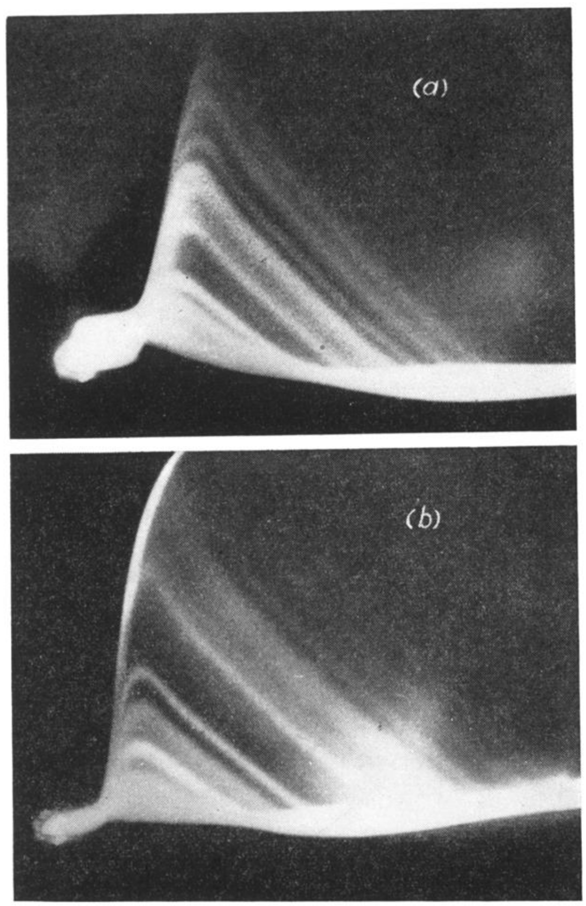

FIG. 12. (a) Photographic representation of Ga^{66}. The three higher energy peaks corresponding to Pair I, Pair II, Photo III appear at the top followed below by the broad Compton distribution of the 2.75-Mev line.

(b) Expanded photographic representation of Ga^{66} emphasizing low energy peaks. The very bright band at the bottom is the annihilation radiation photo-peak. Above it are the Compton distribution and photo-peak of the 1.05-Mev line. There is a gap leading to the 1.73-Mev pair peak which is superposed on the 2.75-Mev Compton distribution.

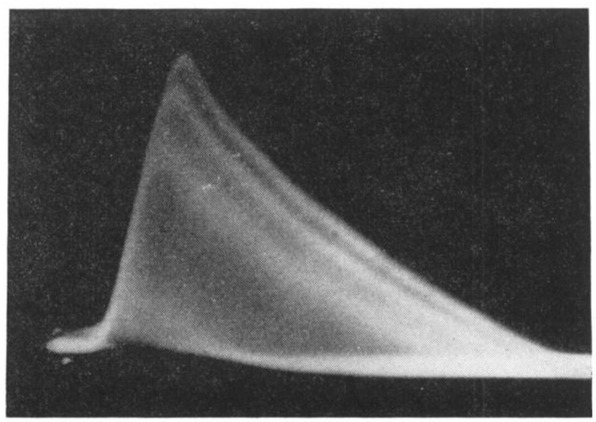

FIG. 13. Co^{60} photographic representation observed with uncollimated source. Weak band near bottom of pattern is a spurious peak produced by backscattered gamma-rays. The two photopeaks are shown at top.

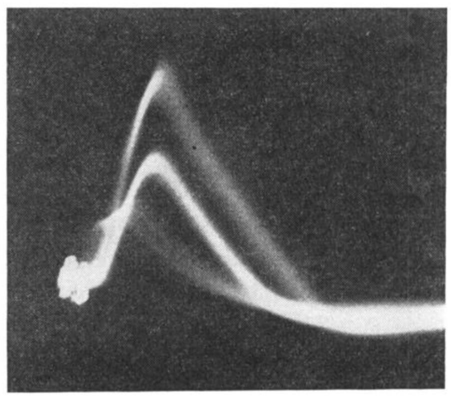

FIG. 14. Double exposure of Au^{198} gamma-rays. Peak at top is due to weak 0.66-Mev gamma-ray present initially to about one part in 250 of the strong 0.411-Mev gamma-ray whose photo-peak stands out sharply in the photograph.

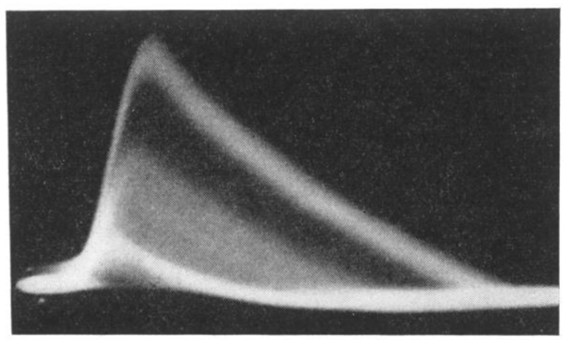

FIG. 6. The pulse distribution for Au^{198} photographed on an oscilloscope screen. The bright band at the top is the photo-peak at 0.411 Mev. Below the gap lies the Compton distribution, with a relatively sharp edge. Superposed on the Compton distribution is a low energy gamma-ray at 0.075 Mev.

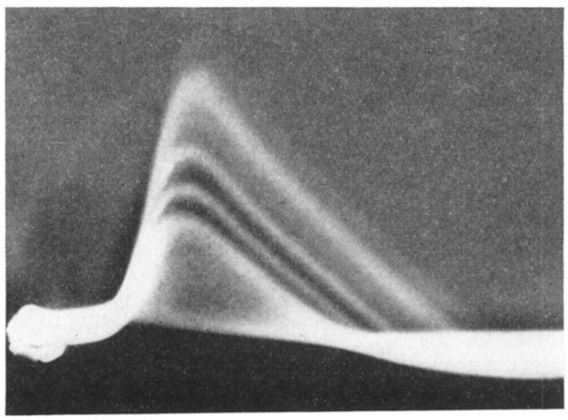

FIG. 7. The pulse distribution for Na^{24} photographed on an oscilloscope screen. The weak 2.76-Mev photo-peak appears at the top. Below it lies the Compton distribution and the prominent pair peak of the 2.76-Mev radiation. Between the pair peak and the Compton edge lies a weak band due to capture of annihilation radiation in the crystal. The photo-peak of 1.38 Mev lies above the continuum due to the Compton effect for 1.38 Mev.

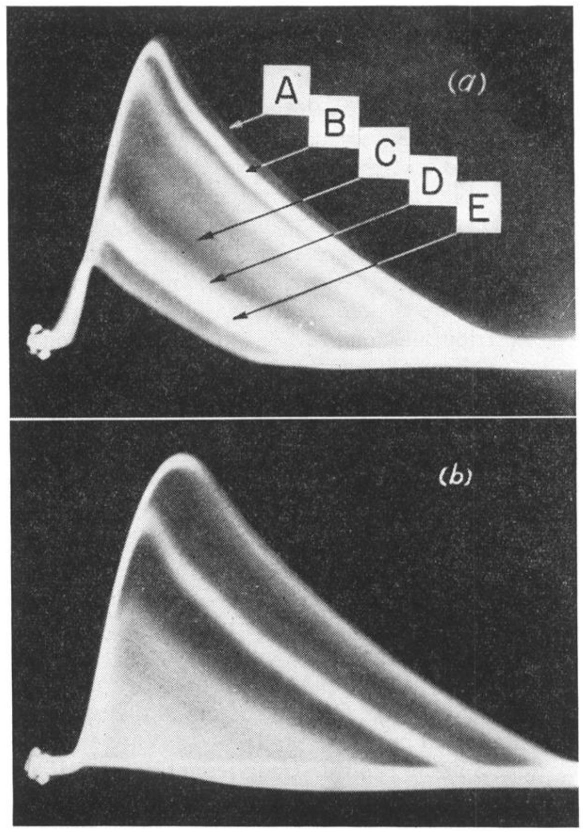

FIG. 9. (a) Photographic representation of Sb^{124}. *A* represents the weak 2.05-Mev photo-line. *B* is the 1.67 photo-line. *C* represents the weak pair line of 2.05 Mev. *D* (see also Fig. 9b) represents the weak 0.73 photo-line and *E* the strong 0.60 photo-line.

(b) Expanded photographic representation of Sb^{124} obtained by increasing the gain of the amplifier. The higher energy peaks are crowded into the topmost edge. The bright band in the middle is the 0.60-Mev photo-line and under it lies the Compton distribution for this line. Above the 0.60-Mev photo-line is the weak 0.73-Mev line observed in Fig. 9a. The unusual crowding of topmost peaks is not typical and resulted from special settings of oscilloscope amplifier gain.