evident that primary extinction is not taking place, since application of Eq. (17) in the range 4.3 to 4.65A, where $\Delta\epsilon > \eta$, yields a cross section $\bar{\sigma} = 0.06$ barn. The grain size of the aluminum is $\sim 2\times10^{-2}$ cm. By increasing η to 2×10^{-3} cm better agreement is obtained.

Figure 4 is a similar curve for Armco iron of $\sim 7\times10^{-3}$ cm grain size, taken by Hughes *et al.* at the Argonne National Laboratory.[7] The presence of extinction is quite apparent. Figure 5 is a curve (taken with the lead crystal) of very finely powdered NaF, together with a theoretical curve calculated from (11). We find good agreement with the theory for negligible extinction.

The determination of the mosaic block size from Eq. (22) requires better resolution than was obtained by the spectrometer used above. A resolution, $\Delta\lambda/\lambda$, of approximately 0.005 is required, whereas we have a resolution of 0.02. Such resolution is feasible and is planned for a future project.

We wish to express our thanks to D. J. Hughes, S. Pasternack, A. W. McReynolds, L. D. Jaffé, J. C. Slater, D. Kleinman, L. Corliss, and J. Hastings for many interesting discussions and suggestions.

[7] Hughes, Wallace, and Holtzman, Phys. Rev. **73**, 1277 (1948).

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Evidence for *K*-Shell Ionization Accompanying the Alpha-Decay of Po^{210}

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The radiations of Po^{210} have been studied using NaI scintillation counters. In agreement with Grace, Allen, West, and Halban, it is concluded that the soft electromagnetic component probably entirely consists of x-rays of lead. The region from 25 kev to 2.5 Mev has been examined and, with the exception of the known γ-ray of 800 kev, no nuclear γ-rays were observed. The ratio of the number of K x-rays to the number of 800-kev γ-rays was measured as 0.134 ± 0.025 to 1. The K shell internal conversion coefficient of the 800-kev transition has been reported as about 0.05, and hence the K x-ray intensity is too great to be explained by internal conversion alone. The residual x-rays are attributed to the process whereby the emission of the alpha-particle causes ionization of the atom. Comparison of the relative intensity of K x-rays and alpha-particles shows qualitative agreement with the probability of this ionization process as calculated by Migdal.

I. INTRODUCTION

ZAJAC, Broda, and Feather[1] have reported γ-rays of energy 84 ± 4 kev in the decay of 138-day Po^{210}. In investigating Po^{210} radiations with NaI scintillation counters we have observed radiation in this energy region, but our measurements yield a mean energy of 76 kev. In attempting to understand the origin of this radiation we have measured its intensity relative to the intensity of the 800-kev γ-ray, and we have looked for coincidences between the 800- and the 76-kev radiations. The results of our investigations are consistent with the interpretation of the softer radiation as x-rays of lead, whereas its interpretation as a nuclear γ-ray would lead to an unlikely decay scheme. The energy resolution of our counters is not sufficient to resolve the K_α and K_β x-rays of lead, and hence we would not be able to distinguish a 76-kev nuclear γ-ray from the lead K x-ray spectrum. However, during the time our measurements were being made, Grace, Allen, West, and Halban[2] reported the result of an investigation of the Po^{210} spectrum where the soft radiations were detected in proportional counters. In their work lines interpretable as the K_α and K_β were observed, and with the help of critical absorption measurements they were determined to be x-rays of lead. Grace *et al.*[2] measured the number of K x-rays relative to alpha-particles and also the number of conversion electrons relative to alpha-particles. Noting that these were experimentally equal they explained the x-rays as the result of the internal conversion of the 800-kev γ-ray.

Our results for the most part are in agreement with the work of Grace *et al.*,[2] but on the question of the relative intensity of K x-rays and conversion electrons we find evidence for more quanta than can be accounted for by internal conversion alone. Since this is the most important contribution of the present paper, we should like to note, as will be shown in the concluding section, that when the data of Grace *et al.*[2] are corrected for the Auger effect and the K/L internal conversion ratio they are not in disagreement with our conclusion.

II. EXPERIMENTAL METHODS

The polonium was supplied by the Eldorado Mining and Refining Company, who report radioactive impurities (of unspecified form) of about 6×10^{-6} mg of Ra-equivalent per millicurie of Po. The sources were prepared for use and further purified by precipitation

* Now at Microwave Laboratory, Stanford University, Stanford, California.
[1] Zajac, Broda, and Feather, Proc. Phys. Soc. (London) **60**, 501 (1948).
[2] Grace, Allen, West, and Halban, Proc. Phys. Soc. (London) **64**, 493 (1951).

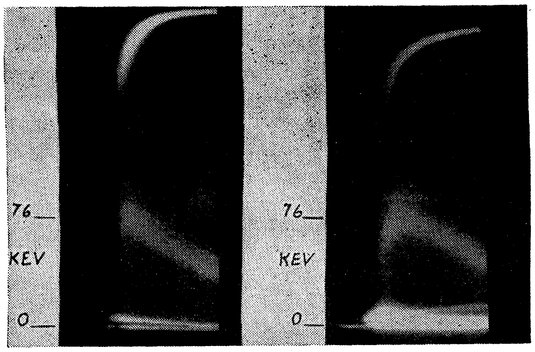

FIG. 1. Photographs of the pulse distributions produced in the same scintillation counter by lead x-rays (left) and Po^{210} (right). Each photograph shows large pulses which overload the amplifier, a band of pulses about 4/10 of full height which are the result of the K x-rays, and small pulses caused by noise and L x-rays.

on nickel foils in 0.1N HCl. Later, some of the polonium was purified a second time in the manner described by Lee and Libby.[3] No spurious lines were observed in the spectra of the sources either before or after purification.

The sources used for alpha-counting were prepared on 0.005-inch foils, thick enough to stop alphas completely, so that only one side was effective for alpha-counting. The activity was found to be somewhat concentrated on the edges of the foil so the edges were trimmed away, leaving a nearly uniform source.

Various sources were used, each with a strength of about one millicurie. The sources were studied using scintillation counters consisting of NaI (Tl) crystals mounted on RCA 5819 photomultiplier tubes. The output of the phototubes was amplified by Model 501 pulse amplifiers and then fed to a differential discriminator, a synchroscope, or in some cases, a coincidence circuit. The power supplies for the electronic equipment were all electronically regulated. Constant voltage transformers were used to stabilize the system against line voltage fluctuations. The final stability was sufficiently good that differential discriminator measurements could be made over periods of one week or more without any significant errors due to instability. The NaI crystals (obtained from the Harshaw Chemical Company) were clear single crystals of about one square cm area and of thicknesses which varied from about 0.2 to 1 cm. The sources were always mounted within one cm of the crystals and no collimation was used.

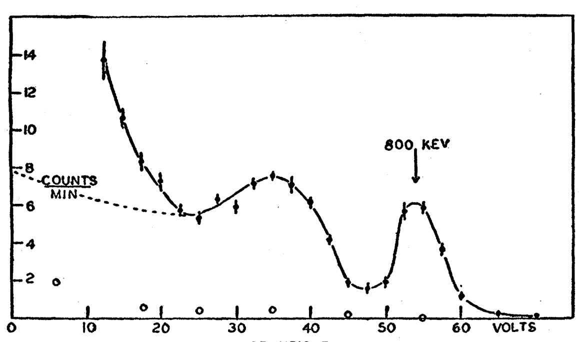

FIG. 2. Differential discriminator curve showing the distribution of pulses resulting from the 800-kev Po γ-ray. The solid curve gives the distribution of pulses due to the source after the background (shown as circles) has been subtracted. Not all of the small pulses are due to the direct effect of the 800-kev γ-ray. The calculated distribution due to this γ-ray only is shown as a dashed curve. The curve was taken with an amplifier gain of 1250 and a 1.5 volt differential discriminator channel width.

When alpha-particles were to be detected, the crystals were cleaved in a dry-box and mounted on a multiplier tube in a box containing silica gel as drying agent. So treated, the crystals could be used for several weeks without appreciable deterioration. When only γ-rays were to be detected, the crystals were further protected by a thin film of mineral oil. Conversion electrons were screened from the crystal by layers of Cellophane or mica. In all cases a film of oil was used to provide good optical contact between the multiplier face and the bottom of the crystal.

Gamma-ray energies were measured by studying the pulse-height distributions either by means of a differential discriminator or by photographing synchroscope presentations of the pulse heights. The details of these measurements followed closely the methods described by Hofstadter and McIntyre.[4]

The relative intensities of the various radiations were determined by measuring the areas under the differential discriminator curves and using calculated values for the efficiency of the NaI crystals for the radiations in question.

III. ENERGY MEASUREMENTS

The pulse distribution produced by the γ-rays of Po^{210} showed clearly the presence of the 800-kev component as well as a component in the energy range reported by Zajac *et al.*[1] No other lines of comparable intensity could be detected in the spectrum which was examined in the range from 25 kev to 2.5 Mev. By comparison with the pulse-height distribution produced in the crystal by incidence of monochromatic x-rays from a calibrated Bragg spectrometer, the mean energy of the softer component was determined as 76±4 kev.

Because 76 kev is approximately the mean energy of the K x-radiation of lead, the daughter element of the polonium decay, we made a direct comparison with the fluorescent x-radiation of lead. Figure 1 shows on the right a photograph of the low energy part of the Po^{210} pulse distribution (exposure time 45 minutes). For comparison Fig. 1 (left) shows a photograph of the pulse distribution of fluorescent lead x-rays, detected in the same crystal under the same conditions. The lead x-rays were produced by exposing a slab of lead placed over the crystals to a strong γ-ray source. The crystal was shielded from the direct γ-rays by several inches of lead. The exposure time was 5 minutes.

The broad line near the center of the polonium

[3] D. D. Lee and W. F. Libby, Phys. Rev. **55**, 252 (1939).

[4] R. Hofstadter and J. A. McIntyre, Phys. Rev. **80**, 631 (1950).

picture is the same height as the K-line in the lead x-ray picture. The band of pulses near the base line of the polonium picture is attributed to L and M x-rays of lead, x-rays of Ni produced by alpha-bombardment of the source backing, and photomultiplier tube noise.

The similarity of the Po radiation and the lead K x-rays has also been checked by taking differential discriminator curves of the two pulse distributions shown in Fig. 1. The resulting curves are similar to Fig. 3. When the two curves are normalized to the same area, subtraction of one from the other yields a curve which is everywhere zero within statistical error.

These experiments do not prove that the soft Po radiations are lead x-rays. However, the results are in agreement with the recent work of Grace *et al.*[2] in which the K_α and K_β lines were resolved by using proportional counters, and were shown by critical absorption measurements to correspond with the x-rays of lead and not of neighboring elements. Neither our experiments nor those of Grace *et al.*[2] rule out the possible

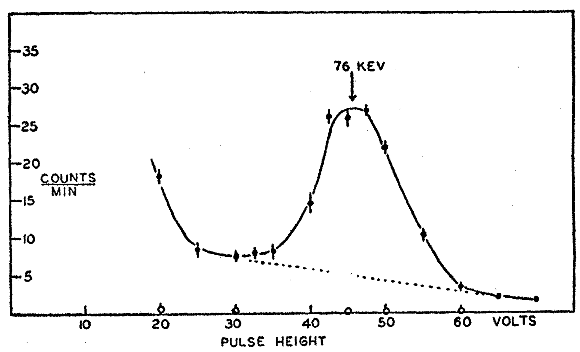

FIG. 3. Differential discriminator curve showing the distribution of pulses resulting from lead x-rays from the Po^{210} source. The curve was taken with an amplifier gain of 10,000 and a 1.5-volt discriminator channel width. The background (shown as circles near the baseline) has been subtracted.

existence of a weak nuclear γ-ray in addition to the lead x-rays. However, the combined experimental results would limit the intensity of a nuclear γ-ray in the 80–90 kev region to less than 10 percent of the K x-ray intensity.

IV. COINCIDENCE EXPERIMENTS

An attempt was made to observe coincidences between the 800-kev and 76-kev radiations by triggering the synchroscope on coincidences between pulses in two crystals, and photographing the pulse-height distributions from either crystal in the usual way. The proper operation of this system and the resolving time of the coincidence circuit (12 μsec) were checked by measuring γ–γ coincidences from a Co^{60} source.

The 76-kev line was observed to be in coincidence with softer radiation, presumably L x-rays, which were also observed in the pulse-height photographs, but was not in immediate coincidence with the 800-kev γ-ray. Because of the low counting rate the presumed K–L

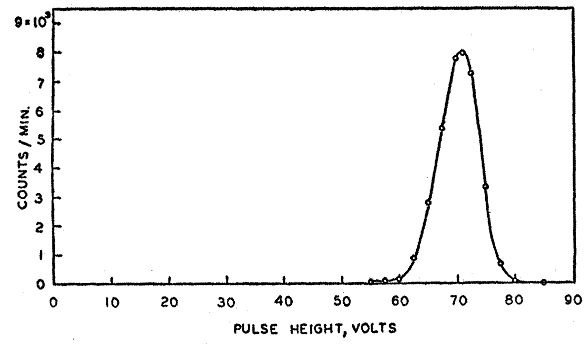

FIG. 4. Differential discriminator curve resulting from Po^{210} α-particles. The discriminator channel width was 1.5 volts and the amplifier gain was about 350.

coincidences were not measured quantitatively. In the case of the 76- and 800-kev quanta the estimated upper limit for the number of coincidences is fewer than 0.05 of the number to be expected if each 76-kev quantum were accompanied by an 800-kev quantum. Thus these radiations could be in cascade only if the lifetime of the intermediate state is considerably greater than the 12×10^{-6} sec resolving time of the coincidence circuit.

V. INTENSITY RATIOS

Figures 2, 3, and 4 show differential discriminator curves which were used in determining intensities of the radiations. A thick crystal was used to determine the relative intensity of the 76- and 800-kev radiations. Figure 2, taken with an amplifier gain of 1250, shows the curve for the 800-kev radiation. Figure 3 was taken with all conditions the same except that the amplifier gain was increased to 10,000 to show the effect of the

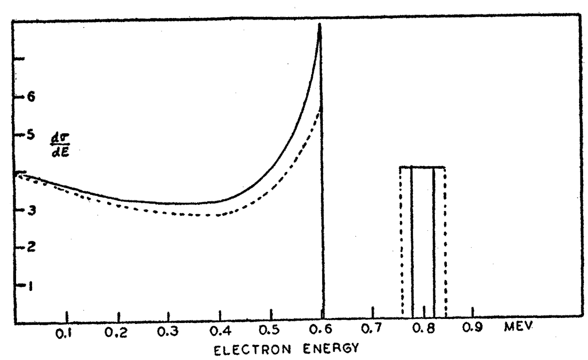

FIG. 5. Energy distribution of electrons produced by an 800-kev γ-ray in a NaI crystal. The solid curve below 0.6 Mev shows the distribution of Compton electrons resulting from the primary interaction only (ordinate scale in arbitrary units). The photoelectric effect gives monoenergetic electrons and is important only for the K-electrons of iodine. The relative number of photoelectrons is given by the area of the solid rectangle at 0.8 Mev. Secondary processes produce electrons which also lose energy in the crystal. The most important secondary process is the capture of Compton scattered photons with the result that the full energy of the γ-ray is spent in ionization of the crystal. The dashed curve shows how this secondary process increases the number of events where the full energy of the γ-ray is expended in ionization at the expense of a loss in number of events where only part of the γ-ray energy is involved.

76-kev radiation. The background when no source was present has been subtracted from both of these curves (the amount of background is shown by the circles at the bottom of the figures).

The low energy part of the 800-kev distribution curve is partly due to the 76-kev line and partly the result of radiation scattered from the brass container which encloses the multiplier and crystal. In order to estimate the part due to the direct effect of the 800-kev radiation, we have made use of the theoretical curves shown in Fig. 5. The solid curve below 600 kev shows the distribution of Compton electrons due to the primary interaction only. The ordinate gives the number of electrons per unit energy interval (arbitrary units) as calculated from the Klein-Nishina formula. In order to show the importance of the photoelectric effect the cross section for the photoelectric absorption in NaI of an 800-kev photon was calculated from the data given by Heitler.[5] In Fig. 5 the relative importance of the photoelectric cross section is indicated by the area of the solid rectangle (should be a delta-function) which is centered at 800 kev.

When γ-rays interact with a NaI crystal multiple processes occur. The most important multiple process

TABLE I. Intensity ratios of the 76- and 800-kev radiations and the alpha-particles.

	N_{76}/N_{800}	N_{76}/N_{α}	N_{800}/N_{α}
Present expts.	0.134 ± 0.025	$2.00\pm0.38\times10^{-6}$	$1.5\pm0.4\times10^{-5}$
Grace *et al.*	0.083 ± 0.03	$1.5\pm0.5\times10^{-6}$	$1.8\pm0.14\times10^{-5}$

is the capture of the scattered photons which result from a primary Compton effect. The result of this process is that pulses corresponding with the full energy of the γ-ray are observed instead of pulses corresponding with the energy of a Compton electron. The magnitude of this effect can be estimated by calculating the expected absorption of Compton scattered photons in the crystal. An experimental check on this calculation is provided by comparison of the number of the observed full energy pulses with the number to be expected due to direct photoelectric absorption. For the crystal used in obtaining the data of Fig. 2, the calculations indicate that the total number of full energy pulses is somewhat more than twice the number due to direct photoelectric absorption. The dotted lines in Fig. 5 show the calculated effect of this multiple process. The area subtracted from the Compton distribution has been added to the rectangle at the full energy. An ideal scintillation counter should reproduce the energy loss curve of Fig. 5. Inhomogeneities in the crystal and the photo surface, together with statistical fluctuations in the counting process, give a spread to the pulses resulting in a distribution like the experimental curve, Fig. 2. We have used the theoretical curve, Fig. 5, to estimate what fraction of the small pulses in Fig. 2 are due to the direct effect of the 800-kev γ-ray. The dotted line in Fig. 2 shows the result.

Since the 76-kev quantum always interacts near the surface of the crystal, whereas the 800-kev penetrates throughout the volume and is only partly absorbed, the counting efficiencies for the two radiations are not the same. The calculation of the efficiencies involves an integration over the volume of the crystal and the area of the source. These calculations have been carried out by numerical integrations which should give an accuracy of better than ten percent for the ratio of the two efficiencies. The absorption coefficient in NaI was taken from x-ray tables as 12.6 cm^{-1} for the 76-kev quanta and 0.244 cm^{-1} (computed from the sum of the theoretical Compton and photoelectric effects) for 800 kev.

In the experiment corresponding to Figs. 2 and 3, the crystal was 1.19 cm by 1.17 cm on the top face and 0.953 cm thick; the source was approximately 0.5 cm square and was centered 0.10 cm above the top face of the crystal. The calculated efficiencies in this case were $\epsilon_{76}=0.41$, and $\epsilon_{800}=0.060$.

Two slight additional corrections must be made to the above calculations: (1) In the 800-kev case the escape from surface layers of the crystal of photoelectrons or energetic Compton electrons has the effect of distorting the electron distribution in Fig. 5 by increasing the relative number of low energy electrons. The importance of this effect was estimated from the average range of the electrons to be about 5 percent. (2) K x-rays of iodine escape from the crystal because the 76-kev quantum is absorbed predominantly by photoelectric effect in the surface layers of the crystal. The escape line was observed in photographs but not measured quantitatively in the present experiments. The process has been studied quantitatively by West, Meyerhof, and Hofstadter,[6] and their unpublished data show that the escape peak is 7 percent of the main peak when 76-kev x-rays are incident. Since our integration of the 76-kev differential discriminator curve did not include the region of the escape peak, we should add 7 percent to the measured area.

Two independent determinations were made of the ratio of the intensities of the 76- and 800-kev radiations. Different sources and crystals were used each time. The experiment corresponding to Figs. 2 and 3 is believed to be the more reliable because the source was repurified one extra time, the geometry was measured more carefully, and greater effort was expended in calculating the efficiency factors. Combining the efficiency factors with the ratio of areas (area 76 kev/area 800-kev$=0.90$) obtained from Figs. 2 and 3 and making the corrections discussed above we get $N_{76}/N_{800}=0.134$ for the relative rate of emission of the 76- and 800-kev quanta.

An early experiment using a different source and slightly different geometry gave $N_{76}/N_{800}=0.14$. This agrees with the later result within the experimental

[5] W. Heitler, *Quantum Theory of Radiation* (Oxford University Press, London, 1944), Chapter III.

[6] West, Meyerhof, and Hofstadter, Phys. Rev. **81**, 141 (1951).

error, but because of the presumed greater reliability of the later experiment we use it as a final result.

The chief sources of error in the determination of this ratio are: (1) uncertainties in the measurement of the crystal and its position relative to the source, (2) approximations in the numerical integration used to calculate counting efficiency, (3) statistical errors in the determination of the differential discriminator curves, and (4) uncertainties in the corrections made necessary by the multiple processes which have been discussed. We estimate that the error could be as high as 10 percent for each of the last three effects and 5 percent for the first; while these are not all random-type errors, we simply have combined them statistically to give the approximate probable error as 18 percent. The final result is then $N_{76}/N_{800}=0.134\pm0.025$.

The number of 76-kev quanta relative to alpha-particles was measured in a similar manner. The source was plated on both sides of a 0.005-inch nickel foil, so that the alpha-particles were only detected from one side while the x-rays were detected from both sides (except for a 6 percent correction for absorption). In order to reduce the alpha-counting rate to a suitable level, a steel shutter 0.0025 cm thick containing a pinhole 0.033 cm in diameter was mounted between the source and crystal. The differential discriminator curve for the alpha-particles, taken with an amplifier gain of about 350, is shown in Fig. 4. (The width of this curve is partially due to straggling and partially due to the fact that the source has finite size and particles from different parts of the source traverse different air paths before striking the crystal.) With the steel shutters blocking the alphas (the absorption of 76-kev quanta in the shutter is negligible) a curve very similar to Fig. 3 was obtained for the 76-kev quanta.

The relative efficiencies of the detector for the alpha-particles and the 76-kev quanta were calculated by numerical integration. In the case of the 76 kev, the calculation is of the same type as described before. In the case of the alpha-particles it is only necessary to average the solid angle, defined by the pinhole, over the area of the source; the geometry was such that all particles passing through the pinhole struck the crystal and were assumed to be counted.

In sweeping the pinhole across the crystal the alpha-counting rate was found to fall off smoothly and symmetrically on either side of a broad central maximum, showing that the crystal could not have had any serious non-uniformities in its surface. The differential discriminator curve was taken at the position of the maximum, corresponding to the assumed condition that the pinhole was centered over the crystal. The source was also checked and found to have the same activity on each side. The calculated efficiency factors are $\epsilon_{76}=0.100$ and $\epsilon_\alpha=1.81\times10^{-4}$. The ratio of the areas under the differential discriminator curves was (area of 76 kev)/(area of α)$=1.93\times10^{-3}$. Making a 6-percent correction for absorption of the x-rays from the back side of the nickel foil, a 7-percent correction for escape of iodine K x-rays in counting 76-kev quanta, and allowing for the fact that only one side of the foil was effective for α-counting, we get

$$N_{76}/N_\alpha=(2.00\pm0.38)\times10^{-6}.$$

The error in this result was estimated on the basis of the same considerations as those described in the determination of N_{76}/N_{800}.

No direct comparison of the 800-kev γ-ray intensity relative to that of alpha-particles was made, but the combination of the last quoted result of the comparison of the 76- and 800-kev intensities gives

$$N_{800}/N_\alpha=(1.5\pm0.4)\times10^{-5}.$$

A comparison of these results with the results for the same ratios as measured by Grace *et al.*[2] is shown in Table I.

Assuming that the 76-kev line is entirely K x-radiation, a correction of 11 percent for the Auger effect as observed in heavy elements[7] gives the results shown in Table II.

VI. CONCLUSIONS

The only radiation in the Po^{210} spectrum which is definitely a nuclear γ-ray is the 800-kev line. If other nuclear γ-rays are present in the range from 25 kev to 2.5 Mev their intensity is less than ten percent of that of the 800 kev γ-ray.

TABLE II. Intensity ratios after correction for the Auger effect.

	N_K/N_{800}	N_K/N_α
Present expts.	0.15 ± 0.028	$2.2\pm0.42\times10^{-6}$
Grace *et al.*	0.093 ± 0.033	$1.7\pm0.56\times10^{-6}$

Our results combined with those of Grace *et al.*[2] indicate that the 76-kev radiation is at least 90 percent and probably entirely due to K-shell ionization, but the observed intensity is too great to be explained by internal conversion of the 800-kev transition, as is shown by the following argument.

The number of K-shell ionizations due to internal conversion divided by the number of γ-rays is equal to the internal conversion coefficient, α_K. The total conversion coefficient of the 800-kev γ-ray has been measured (by counting the number of electrons relative to γ-rays) as 0.067 ± 0.017 by Grace *et al.*[2] and as less than 0.05 by Alburger and Friedlander,[8] who also measured the K/L ratio as 3.7. The value of the K/L ratio is highly accurate, and therefore α_K is not over 3.7/4.7 times the total conversion coefficient. According to Grace *et al.*[2] α_K is then 0.053 ± 0.013 and less than 0.04 according to Alburger and Friedlander.[8] Both of these numbers are considerably less than our result, 0.15 ± 0.028 for the total number of K-shell ionizations relative to γ-rays, and are also probably less than the result, 0.093 ± 0.033, for the same quantity as determined from the measurements of Grace *et al.*[2]

[7] L. S. Germain, Phys. Rev. **80**, 937 (1950).
[8] D. E. Alburger and G. Friedlander, Phys. Rev. **81**, 141 (1951).

The above calculations indicate that only about one-third or one-half the K-shell ionization can be attributed to internal conversion. The remaining ionization is probably the direct result of the emission of the alpha-particle.

Assuming that the excess K-shell ionization is due to the direct action of the alpha-particle as it leaves the atom, the probability of this process is given by the quantity N_K/N_α multiplied by the fraction of K-shell ionizations not due to internal conversion. Using our values for N_K/N_{800} and N_K/N_α together with the value $\alpha_K=0.053\pm0.013$, we arrive at

$$(2.2\pm0.4)\{1-(0.053\pm0.013)/(0.15\pm0.028)\}\times10^{-6} = (1.4\pm0.35)\times10^{-6}$$

for the probability of K-shell ionization by the alpha-particle.

Migdal[9] has made theoretical calculations of the probability of ionization of the daughter atom by a particle which leaves the nucleus. Migdal's theory predicts that the alpha-particle almost always ionizes the atom, but that the ionization probability of a given electron shell decreases rapidly as shells nearer and nearer the nucleus are considered.

The process of direct ionization by the alpha-particle has been suggested as the origin of the L x-rays which are observed in Po^{210} radiations.[10,11]

[9] A. Migdal, J. Phys. (U.S.S.R.) 4, 449 (1941).
[10] I. Curie and F. Joliot, J. phys. et radium 2, 20 (1931).
[11] W. Rubinson and W. Bernstein, Phys. Rev. 82, 334 (1951).

The approximations made in Migdal's calculations include the use of perturbation theory to describe the effect of the alpha-particle, the assumption that the alpha-particle moves with uniform velocity as it leaves the nucleus, and the use of nonrelativistic hydrogen-like wave functions to describe the atom. These approximations are best in the case of K-shell ionization, but even here the error may be appreciable. Migdal's result for the probability of ionization of the K-shell is 2.2 $(137\ v_\alpha/Z^2c)^2$, where v_α is the velocity of the alpha-particle and Z is the atomic number of the daughter atom. Evaluation of this expression gives 2.6×10^{-6} in the case of Po^{210}.

Migdal's theory thus agrees in order of magnitude with the experimental results, $(1.4\pm0.35)\times10^{-6}$, but the predicted ionization probability is too high to be reconciled with either our results or those of Grace *et al.*[2] Since Migdal's theory neglects the effects of screening of the nucleus from the K electrons, one might argue that the Z in Migdal's theory should be replaced by a smaller "effective" Z. This change would make the predicted ionization probability even higher and thus would increase the discrepancy with experiment. The authors believe that approximations in Migdal's theory may result in an overestimate of the K-shell ionization process.

The authors would like to express their appreciation to Professors R. Hofstadter and W. E. Meyerhof for their valuable suggestions and criticisms concerning this work.

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The Sign of the Quadrupole Interaction Energy in Diatomic Molecules*†

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(Received January 9, 1952)

The molecular beam magnetic resonance method has been used to determine the sign (and the magnitude in those cases where it has not been previously measured) of the quadrupole interaction energy of the alkali nuclei in the homonuclear molecules, that of Na^{23} and Li^7 in the alkali halides, and that of Cl^{35} and Cl^{37} in KCl. An obstacle is inserted into the path of the beam so that its edge coincides with the position of the undeflected beam. Molecules of either positive or negative total magnetic moment are then removed from the beam which arrives at the detector. Certain maxima in the nuclear resonance spectrum at high magnetic fields $(eqQ\ll g_I\mu_0H)$ arising from the transitions $\Delta m_I=\pm1$ are suppressed depending on the states removed by the obstacle. It is thus possible to identify the resonance maxima in terms of the transitions which produce them. From this evidence the sign of the quadrupole interaction energy can be deduced. The quadrupole interaction energy, eqQ, is positive for Li^7 and negative for Na^{23} in the homonuclear and the halide molecules. These results suggest that the sign of q at a given nucleus is the same in a rather considerable range of diatomic molecules. The interaction constant, eqQ, is positive for Cs^{133} in Cs_2, and negative for K^{39} in K_2, Rb^{85}, Rb^{87} in Rb_2, and Cl^{35}, Cl^{37} in KCl. The signs of the interaction for K^{39}, Rb^{85}, Rb^{87}, and Cs^{133} in the alkali fluorides, and for Cl^{35}, Cl^{37} in TlCl as determined by the molecular beam electrical resonance method are the same as those for the same nucleus in the molecules here considered.

INTRODUCTION

It is the purpose of the present paper to discuss in detail a method which permits the determination of the sign of the quadrupole interaction energy in diatomic molecules and to present the results of new measurements on the sign and the magnitude of the quadrupole interaction energies of several nuclei in a considerable range of diatomic molecules. A preliminary description of the method has previously been given.[1]

Unfortunately it is not possible, in general, to deduce

* This research was supported in part by the ONR.
† Submitted by R. A. Logan in partial fulfillment of the requirements for the degree of Doctor of Philosophy, in the Faculty of Pure Science, Columbia University.

[1] P. Kusch, Phys. Rev. 76, 138 (1949).

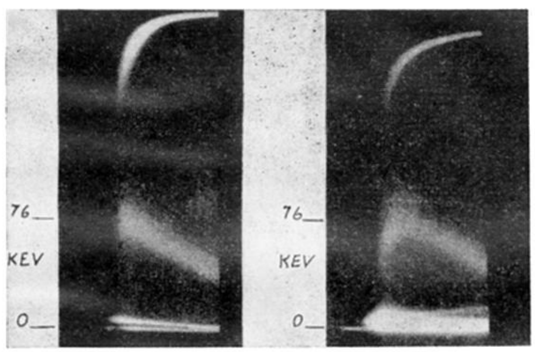

FIG. 1. Photographs of the pulse distributions produced in the same scintillation counter by lead x-rays (left) and Po^{210} (right). Each photograph shows large pulses which overload the amplifier, a band of pulses about 4/10 of full height which are the result of the K x-rays, and small pulses caused by noise and L x-rays.