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Decay of Bi^{207}

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Bi^{207} has been found to decay by electron capture accompanied by gamma rays of energies 0.569 ± 0.0015, 0.894 ± 0.007, 1.0639, 1.43 ± 0.01, and 1.771 ± 0.005 Mev having transition intensities of 100:0.16:87:0.16:8 percent per disintegration, respectively. K-conversion electron intensities are 1.7, 0.0039, 8.2, 0.0009, and 0.022 electrons per 100 disintegrations respectively. The 0.894, 1.43 and 1.771-Mev transitions have K-conversion coefficients of $(2.4\pm1)\times10^{-2}$, $(5\pm2)\times10^{-3}$ and $(2.5\pm0.5)\times10^{-3}$. The first of these is in agreement with $M1$ radiation and the latter two with $E2$ or $E2+M1$ radiations. Electron capture branches are 87 percent to the $i_{13/2}$ state at 1.633 Mev, 5 ± 2 percent to the 0.57-Mev first excited state and 8 ± 2 percent to a level at 2.35 Mev. Branching to the 2.35-Mev level proceeds only by L-capture as shown from the x-ray spectrum in coincidence with 1.78+0.57 Mev photopeak sum pulses. The decay energy to the 2.35-Mev level thus lies between 15 and 90 kev and the total Bi^{207} decay energy is 2.40 ±0.04 Mev. Gamma-gamma and electron-gamma correlation experiments confirm the 1.06–0.57 Mev cascade as $13/2\rightarrow5/2\rightarrow1/2$ while the 1.78–0.57 Mev gamma-gamma correlation is isotropic to within 5 percent. A spin $\geq7/2$ for the 2.35 Mev state is supported by a crossover intensity of $<6\times10^{-5}$ per disintegration as determined with a photoneutron detector. An assignment of $f_{7/2}$ to the 2.35 Mev level is compatible with all of the data including the 1.78–0.57 Mev angular correlation, if the 1.78-Mev transition is assumed to consist of a mixture of $\sim$94 percent $E2$ and $\sim$6 percent $M1$. Fast-coincidence techniques have been used to show that the 0.57-Mev level has a lifetime of $<4\times10^{-10}$ sec.

INTRODUCTION

THE energy levels of Pb^{207}, a nucleus having one neutron less than a closed shell, should be describable[1,2] according to the shell model in the same way as for a system with one nucleon outside of a closed shell. On the basis of a Pb^{207} level arrangement similar to the one proposed in this paper except for the configuration assignment of the state at 2.35 Mev (formerly assumed to be $h_{9/2}$), theoretical calculations were made by Pryce[1] on the levels expected in the "two-hole" nucleus Pb^{206}. These calculations were correlated successfully with the experimentally observed states. We shall describe a number of recent results according to which the probable assignment to the 2.35-Mev level in Pb^{207} is $f_{7/2}$ and which reveal other interesting features of the Bi^{207} decay. The effect of the $f_{7/2}$ assignment on the predicted levels in Pb^{206} will be discussed later.

Bi^{207} was discovered[3] by Neumann and Perlman who found that it decays by electron capture to Pb^{207} with a half-life of approximately 50 years. They reported that the decay is accompanied by eight gamma rays, four of which lie above 2 Mev, as observed from the internal conversion electron spectrum. A much shorter Bi^{207} half-life, 8.0 ± 0.6 years, has been published[4] recently by Cheng *et al.* Wapstra[5] and McGowan and Campbell[6] confirmed the presence of only two transitions of energies 0.56 and 1.06 Mev. Wapstra also proposed that the electron capture of Bi^{207} branches 80 percent to a level at 1.625 Mev in Pb^{207} and 20 percent to a level at 0.565 Mev.

Earlier it had been found[7] that a 0.8-sec isomeric state is excited in Bi^{207} decay. This was identified as resulting from the 1.06-Mev transition by Goldhaber and Sunyar,[8] who gave it an $M4$ assignment on the basis of lifetime and energy. The high energy and large conversion coefficient has made this transition useful[9] as an energy standard in beta spectroscopy.

That the 1.06–0.57 Mev main cascade is probably an $M4-E2$ cascade was confirmed by the conversion coefficients measured by Wapstra[5] and by McGowan and Campbell.[6] The angular correlation experiments of McGowan and Campbell[6] established the spin sequence as $13/2\rightarrow5/2\rightarrow1/2$, the shell-model assignments being $i_{13/2}\rightarrow f_{5/2}\rightarrow p_{1/2}$. The latter workers also observed a 1.76-Mev gamma ray in their scintillation spectrum, but did not assign this to Bi^{207}, and placed a very low limit on the intensity of any higher-energy gamma rays.

Prescott has reported[7] Bi^{207} gamma rays of 0.57, 1.07, 1.76, and 2.47 Mev with evidence for a prompt gamma ray of 1.46 Mev. From coincidence data he suggests that the 1.07-Mev line may actually be double, 6 percent of it being in prompt coincidence with electron capture.

Other evidence on the Pb^{207} levels comes from the beta decay[10] of Tl^{207} which excites a level at 0.87 Mev and from the alpha decay[11] of Po^{211} to levels at 0.56, 0.87, and 1.63 Mev. (d,p) and (d,t) nuclear reaction experiments by Harvey[12] are also consistent with Pb^{207} levels at 0.56, 0.89, 1.63, and 2.33 Mev as well as others at higher energies.

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* Under contract with the U. S. Atomic Energy Commission.

[1] D. E. Alburger and M. H. L. Pryce, Phys. Rev. **95**, 1482 (1954).

[2] M. H. L. Pryce, Proc. Phys. Soc. (London) **A65**, 773 (1952).

[3] H. M. Neumann and I. Perlman, Phys. Rev. **81**, 958 (1951).

[4] Cheng, Ridolfo, Pool, and Kundu, Phys. Rev. **98**, 231(A) (1955).

[5] A. H. Wapstra, Arkiv Fysik **7**, 279 (1954).

[6] F. K. McGowan and E. C. Campbell, Phys. Rev. **92**, 523 (1953); F. K. McGowan, Phys. Rev. **92**, 524 (1953).

[7] J. R. Prescott [Proc. Phys. Soc. (London) **A67**, 540 (1954)] gives a more complete review of previous evidence on Bi^{207} decay.

[8] M. Goldhaber and A. W. Sunyar, Phys. Rev. **83**, 906 (1951).

[9] D. E. Alburger, Phys. Rev. **92**, 1257 (1953).

[10] J. Surugue, J. phys. radium **7**, 145 (1946).

[11] Jentschke, Juveland, and Kinsey, Phys. Rev. **96**, 231 (1954).

[12] J. Harvey, Can. J. Phys. **31**, 278 (1953).

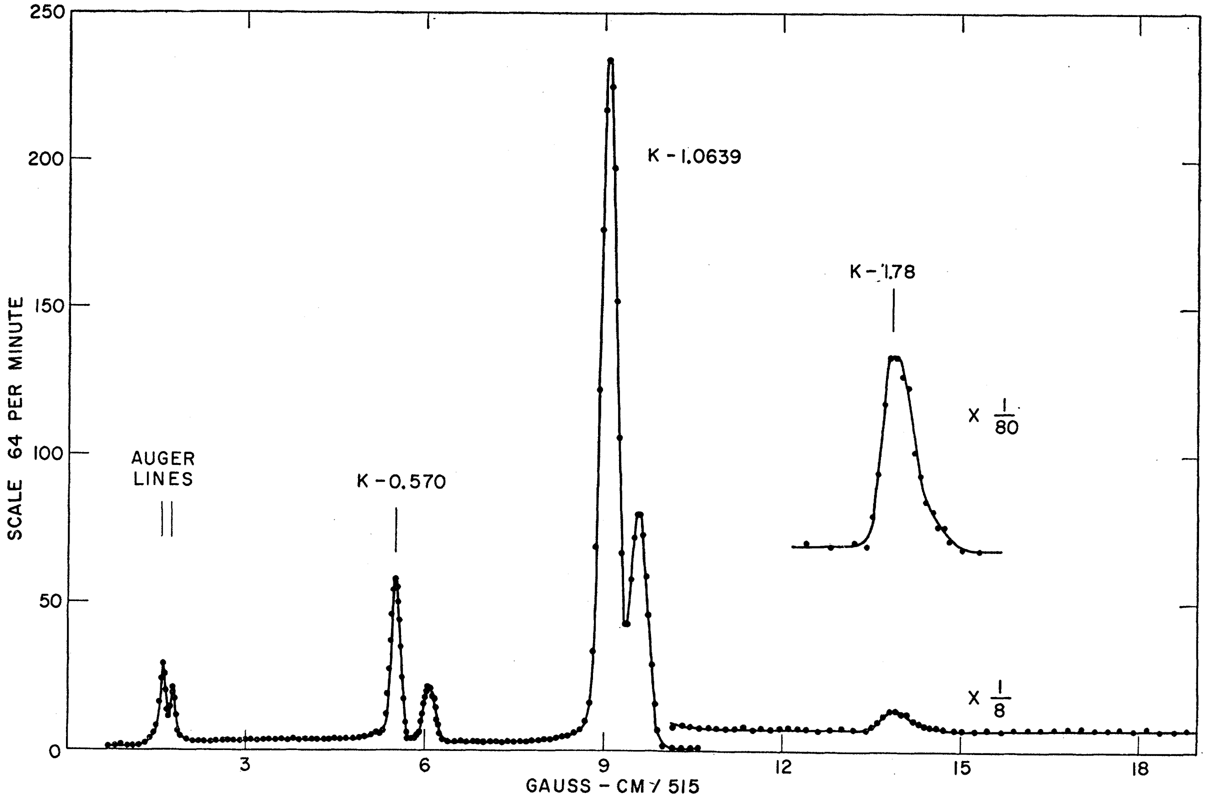

FIG. 1. Internal conversion spectrum of Bi^{207} using a 36-μC source at 3.7 percent resolution.

CONVERSION ELECTRON AND GAMMA RAY SPECTRA†

Most of the experiments to be described were made on sources taken from 2.5 mC of Bi^{207} activity which had been prepared by a 9000 μa-hour 22-Mev deuteron bombardment of ordinary lead in the Oak Ridge cyclotron, carried out in July, 1953. Subsequent chemical separations[13] were made at Brookhaven. Since all of the experiments were performed at least 8 months after bombardment, 6-day Bi^{206} and 14-day Bi^{205} had decayed to negligible proportions.

The conversion electron spectrum from a 36-μC source of Bi^{207} electroplated on a 10-mg/cm^2 Cu backing was examined in the Brookhaven lens spectrometer with the results shown in Fig. 1. Auger lines and conversion electrons corresponding to transitions of 0.57, 1.06, and 1.78 Mev are indicated. Of the conversion lines above 1.8 Mev reported[3] by Neumann and Perlman, the weakest would have been 6 times the probable errors of the points in the corresponding region of Fig. 1 and their *K*-1.46 line would have been 10 times as large as the *K*-1.78 line. Relative conversion intensities were checked 9 months after the data of Fig. 1 with the same results.

A more thorough search for weak conversion electrons between *L*-0.57 and *K*-1.06 and between *L*-1.06 and *K*-1.78 was carried out with a 150-μC source at a resolution of 4 percent. In the lower of these two energy regions the scattered tail of the *K*-1.06 line hindered the measurements. However, there seemed to be slight evidence of a line corresponding to a transition of about 0.9 Mev. If such a line is present its intensity is ≤ 0.1 percent of *K*-1.06. Figure 2 shows the higher-energy region obtained for one of two different source geometries, both of which gave comparable results. A line is observed which, if it is real, corresponds to a transition of 1.44 Mev and has a *K*-conversion intensity 4 ± 1 percent as strong as *K*-1.78. Since its intensity is a factor of 10^4 weaker than *K*-1.06 there is a possibility that the line is a ghost arising from scattering effects. In any case, the quoted intensity can be considered as an upper limit.

If the *K*-conversion intensities are normalized on the assumption that the 0.57-Mev transition is pure *E*2 and occurs once per disintegration, then the 0.57, 1.0639, 1.44, and 1.78-Mev transitions have *K*-line intensities of 1.7, 8.2, 0.0009, and 0.022 electrons per 100 disintegrations. A correction of 10 percent in the *K*-1.78 peak height has been made because of the unresolved *L*-electron contribution.

Energy values for the 1.44 ± 0.015 and 1.78 ± 0.01 Mev gamma rays were obtained from the data of

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† See note added in proof on page 702.

[13] D. E. Alburger and G. Friedlander, Phys. Rev. 81, 523 (1951).

Fig. 2. The 569±1.5 kev gamma-ray energy[14] was determined at 1.2 percent resolution with a 13-microcurie source 3 mm in diameter by comparing its K-conversion peak and extrapolated edge positions with those of the 1.0639-Mev gamma ray.

A K/L ratio measurement on the 0.57-Mev gamma ray was carried out at 1.4 percent resolution. The M line is then sufficiently well resolved to make a negligible contribution to the L peak height. A ratio 3.4±0.4 is obtained which agrees well with the theoretical $K/L_{\mathrm{I+II+III}}$ ratio of 3.2 calculated for a 0.57-Mev $E2$ transition at $Z=85$ from L-shell conversion tables privately distributed by Rose, Goertzel, and Swift. In a previous report[9] the K/L ratio of the 1.06-Mev transition was given as 3.95±0.25. Since the L_{II} conversion coefficient at 2.0 mc^2 is not yet available it is only possible to estimate by extrapolation that the $K/L_{\mathrm{I+II+III}}$ ratio at $Z=85$ and 2.0 mc^2 (1.022 Mev) for an $M4$ transition is between 3.5 and 4. Hence both K/L ratios are consistent with the $E2$ and $M4$ assignments to the 0.57- and 1.06-Mev gamma rays, respectively.

The unconverted gamma-ray spectrum, measured with 1 in.×1½ in. and 2 in.×2 in. NaI crystals, showed prominent Compton and photo distributions for the 0.57-, 1.06-, and 1.78-Mev gamma rays. With a 36-μC source 10 in. from the 1 in.×1½ in. crystal the yield at high energies dropped off by a factor of 500 below the 1.78-Mev peak intensity. From the full-energy peak efficiency as a function of gamma-ray energy, calculated with the total efficiency tables[15] of McGowan and the peak-to-total curve[16] of Heath, Bell, and Davis, the maximum possible intensity of any gamma ray between 2 and 2.5 Mev is 1 per 2000 disintegrations. Correcting for efficiency and internal conversion it is found that the 1.06- and 1.78-Mev transitions have intensities of 88 percent and 9 percent of the 0.57-Mev line, respectively.

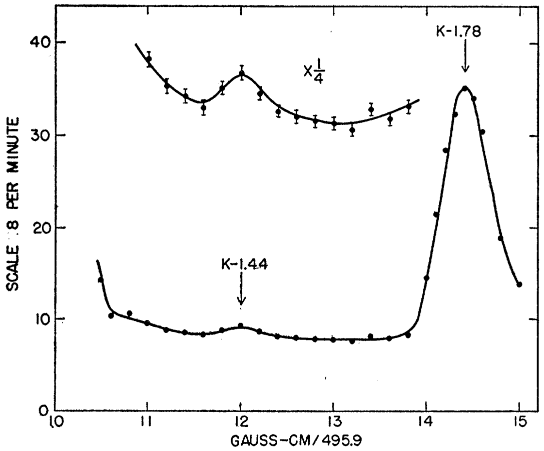

FIG. 2. Conversion electrons above 1.1 Mev measured at 4 percent resolution, showing the presence of a weak K-1.44 line.

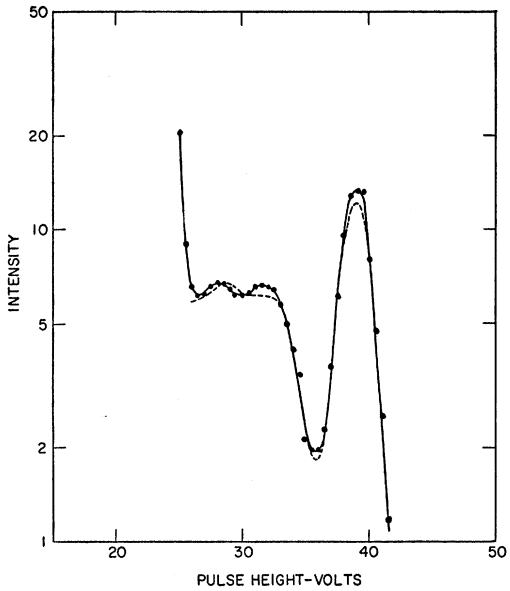

FIG. 3. Singles scintillation spectrum above 1 Mev of Bi^{207} (solid curve) and Y^{88} (dashed curve).

A more detailed study of the scintillation spectrum above 1 Mev was carried out with an Atomic Instruments Company 20-channel pulse-height analyzer. In order to establish the pulse-height distribution for a gamma ray of about 1.8 Mev, a source of Y^{88} was prepared by deuteron bombardment of Sr followed by chemical separation. This activity has been reported[17] as emitting gamma rays of 0.908 and 1.853 Mev of equal intensity and a 2.76-Mev gamma ray of 1 percent intensity. Comparisons of the energies of the Y^{88} and Bi^{207} lines were made both with a gray-wedge analyzer, using microscope reading of Polaroid photographs, and with the 20-channel analyzer. The same total counting rates were maintained in the Dumont 6292 phototube output. These precautions were taken because of studies of peak shifts with counting rate made recently[18] by Bernstein. It was found that the Y^{88} gamma is 2.8 percent higher in energy than the 1.78-Mev Bi^{207} line. This places it at 1.83 Mev based on the Bi^{207} energy. The region above 1.8 Mev did not show a well-defined line of 2.76 Mev which could be distinguished from pulse pile-up. Our work suggests that the 2.76-Mev Y^{88} gamma ray, if present, is ≤0.5 percent as intense as the 1.83-Mev gamma ray. Hence the effect of its pulse-height distribution on that of the 1.83-Mev gamma ray is negligible.

Comparisons of the Bi^{207} and Y^{88} scintillation spectrum shapes were made using liquid sources of equal volume in identical weighing bottles. Approximately

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[14] P. Marmier and F. Boehm of the California Institute of Technology have determined the energy of this transition to be 569.7±0.2 kev (private communication).

[15] F. K. McGowan (privately circulated tables); see Phys. Rev. **93**, 163 (1954).

[16] Heath, Bell, and Davis, Oak Ridge National Laboratory Report ORNL 1415 (unpublished).

[17] Hollander, Perlman, and Seaborg, Revs. Modern Phys. **25**, 469 (1953).

[18] W. Bernstein (unpublished).

equal strengths of 1.8-Mev radiation were present in both samples. Gains were adjusted so that the photo peaks of the 1.78- and 1.83-Mev gammas occurred in the same channel and runs were made with and without lead collimation, using both size crystals. In all cases, the Bi^{207} curve exhibited an excess "hump" at the peak of the 1.78-Mev Compton distribution. A typical set of curves taken with a $\frac{3}{8}$-inch diameter Pb collimator 8 cm long is shown in Fig. 3. The dashed curve for Y^{88} has been matched so that the full-energy-loss peak occurs at the same pulse height as that for Bi^{207}, and such that the amplitudes of the curves are the same in the vicinity of the one-annihilation-quantum escape peak. The fact that the one-escape peaks do not occur at exactly the same pulse height is explained by the 2.8 percent energy difference of the gamma rays. This energy difference also accounts for the slightly lower relative height of the Y^{88} full-energy-loss peak. However, it is not expected that the shape of the Compton distribution would change appreciably for such a small change of energy. Based on the normalization shown, the extra hump in the Bi^{207} curve corresponds to the full-energy-loss peak of a 1.44-Mev gamma ray whose intensity is 2.5 percent of the 1.78-Mev gamma-ray intensity.

Pile-up of the relatively stronger 0.57- and 1.06-Mev gamma-ray distributions of Bi^{207} were considered for their effect on the 1–1.8 Mev region. The sum energy of 1.63 Mev occurs at the trough of the 1.78-Mev pulse-height distribution and this point would be expected to be most sensitive to pile-up. For a variation of a factor of 6 in counting rate as used in the various runs, there was no essential change in the peak-to-trough ratio for the 1.78-Mev gamma ray. It is concluded that pile-up could not account for the difference between the Bi^{207} and Y^{88} curves in the neighborhood of the 1.44-Mev photoline. Pulse addition can also be neglected since the peak-to-trough ratio of the 1.78-Mev gamma ray remained constant for source-to-crystal distances as great as 25 inches. The trough of the 1.63-Mev pulse addition distribution occurs near 1.4 Mev and cannot appreciably influence the 1.44-Mev photopeak intensity.

The lens spectrometer and 1 in.$\times 1\frac{1}{2}$ in. NaI crystal data, together with the known conversion coefficients of the 0.57- and 1.06-Mev transitions, can be used to derive the K-conversion coefficients of the 1.44- and 1.78-Mev gamma rays. These are found to be $(5\pm2)\times10^{-3}$ and $(2.5\pm0.5)\times10^{-3}$, respectively. If the adopted branching of 8 percent to the 2.35-Mev level (see Fig. 7) is used rather than the gamma ray data alone both of these coefficients are 10 percent higher. As a check on the 0.57- and 1.06-Mev K conversion and gamma-ray intensity data, the ratio of K-conversion coefficients of 1.06/0.57 can be calculated from the ratio $K\text{-}1.06/K\text{-}0.57=4.8$ derived from Fig. 1 and the gamma-ray intensity ratio from the NaI crystal data. The result is 5.98 compared with a theoretical[19] conversion coefficient ratio of 6.03 if the transitions are assumed to be pure $M4$ and $E2$ respectively. Independently of the NaI gamma-ray measurements, the relative transition intensities of 1.06/0.57 can be calculated from the ratio 4.8 of the K-conversion line intensities, again based on the assumed multipolarities $M4$ and $E2$. The result is that the 1.06/0.57 transition ratio is 0.89 ± 0.04.

COINCIDENCE MEASUREMENTS

Gamma-gamma coincidence experiments were carried out using two 2 in.$\times$2 in. NaI crystal detectors and Bi^{207} sources of 0.18, 0.44, and 1.0 microcurie. In the first tests one counter was channeled on either the 0.57- or 1.06-Mev line and the coincidence spectrum was scanned in the other detector by using a single-channel pulse-height analyzer. It was found that the 0.57-Mev transition is in coincidence with both the 1.06- and 1.78-Mev gamma rays but that the latter two are not in coincidence with each other.

A search was then made with a coincidence gray-wedge analyzer[20] for possible gamma rays of 1.44 and 0.9 Mev. The same detectors as above were used except that a Pb absorber sandwiched with brass was included between the crystals in order to reduce spurious effects arising from addition of back-scattered Compton gamma rays in the display crystal. With the channel in the 900-kev region the photo peak of a gamma ray of 1.44 Mev was observed to be in coincidence. When the channel was set for pulses greater than 1.3 Mev a photopeak of about 0.9 Mev was found. From the calibration of the gray wedge the 1.44–0.9 Mev coincidence intensity was estimated to be 2 ± 1 percent as strong as the 1.78–0.57 Mev coincidence intensity.

The above experiments were repeated using a geometry improved so as to further reduce back-scattering addition effects. Also in order to obtain more quantitative results the coincidence spectra were recorded with a 20-channel pulse-height analyzer. These data are illustrated in Figs. 4 and 5. Gamma rays of 1.44 and 0.90 ± 0.02 Mev were observed, and their coincidence intensities after corrections for efficiencies were found to be slightly greater than 2 percent of the 1.78–0.57 Mev coincidence intensity. In some of the experiments a Bi^{207} source was used which had been prepared in December, 1952 at the Nobel Institute of Physics. Inasmuch as this source displayed the 1.44–0.90 Mev cascade with the same relative intensity as in sources from the Oak Ridge bombardment, it is plausible to assume that the results do not arise from impurities and that the 1.44–0.90 Mev cascade actually belongs to Bi^{207}. On the basis of the singles and coincidence

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[19] Rose, Goertzel, Spinrad, Harr, and Strong, Phys. Rev. **83**, 79 (1951).

[20] Bernstein, Chase, and Schardt, Rev. Sci. Instr. **24**, 437 (1953); R. L. Chase, Brookhaven National Laboratory Report 263 (1954) (unpublished); A. W. Schardt, Brookhaven National Laboratory Report 237 (1954) (unpublished).

data, we adopt for the 1.44-Mev gamma ray an intensity 2.0±0.6 percent of the 1.78-Mev transition intensity, or 0.16 percent per disintegration.

The capture process to the 2.35-Mev level was studied by observing the x-ray spectrum in coincidence with the (1.78+0.57)-Mev photo sum peak, thereby avoiding all x-rays associated with internal conversion. For detection of the x-rays a NaI crystal 2 mm thick and 1 inch square was used. It was necessary to channel the gamma-ray counter on the 2.35-Mev full-energy peak and not to include any of the sum Compton distribution since the latter has associated with it back scattered gamma rays which can be detected in coincidence by the x-ray crystal. This experiment showed that only *L* x-rays are in coincidence with the sum peak and that there is at most a 2 percent *K* x-ray coincidence intensity. If one assumes an *L* fluorescent yield of 0.40, the maximum number of *K*-shell vacancies is 1 percent of the total capture to the 2.35-Mev state.

Possible electron capture to the 0.57-Mev level of Pb^{207} was investigated by measuring the 0.57- and 1.06-Mev gamma-ray spectra in coincidence with *K* x-rays. Since the 1.06-Mev gamma ray follows an 0.8-sec isomeric state, the only possible *K* x-ray coincidences arise from internal conversion of the 0.57-Mev gamma ray. On the other hand, the 0.57-Mev state can be fed in three ways, i.e., by the 1.78- and 1.06-Mev transitions and by possible electron capture. It has already been shown that the 2.35-Mev level is formed only by *L* capture and furthermore that the conversion of the 1.78-Mev gamma ray is very small. Hence the feeding of the 0.57-Mev level by the 1.78-Mev transition will result in a negligible number of coincidences between *K* x-rays and 0.57-Mev gamma rays.

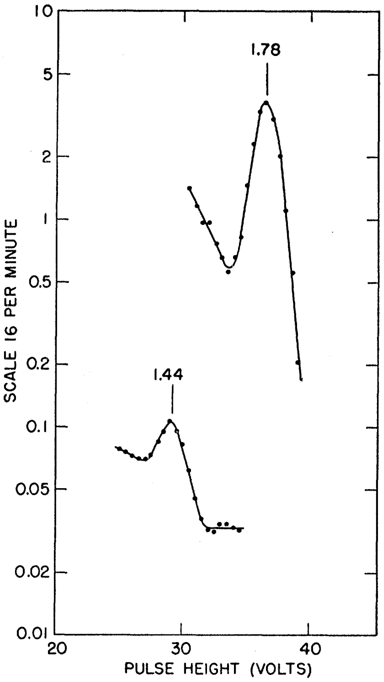

FIG. 5. Upper curve — coincidences with a channel set on 0.57 Mev. Lower curve — coincidence yield when the channel is centered at 0.90 Mev, showing a 1.44-Mev photo line.

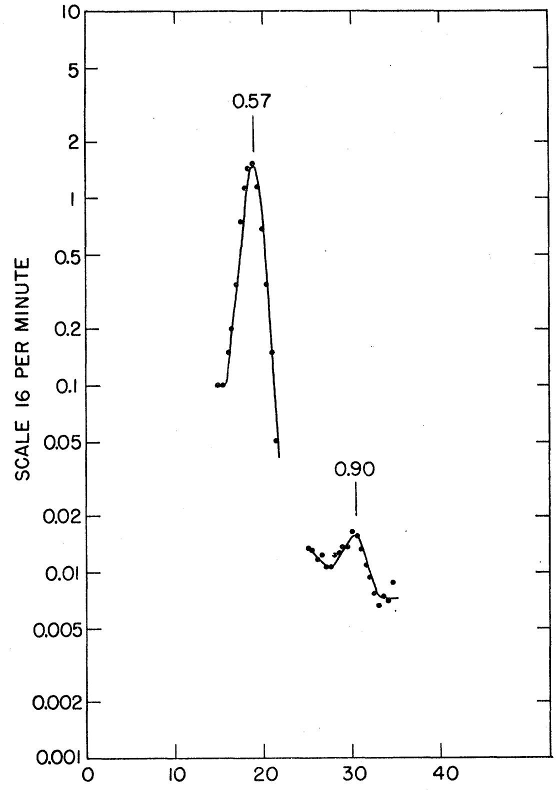

FIG. 4. Pulse-height spectrum in coincidence with a channel set for >1.3 Mev. The 0.57-Mev peak arises from coincidences with 1.78-Mev gamma rays and the 0.90-Mev peak is associated with 1.44-Mev gamma rays.

The magnitude of the net *K* x-ray—0.57-Mev gamma-ray coincidence yield can be deduced from the coincidence measurements listed in Table I. In deducing the net *K* x-ray—0.57-Mev gamma-ray coincidence yield, a small correction has to be made for the difference between the Compton distribution under the photopeak from that measured just above the photopeak. A similar set of experiments involving *K* x-rays and the 1.06-Mev photopeak gives the net *K* x-ray—1.06-Mev gamma-ray coincidence yield. The ratio of 570-kev to 1.06-Mev photopeak yields within the channels is measured in the same experiment and must be corrected for the Bi^{207} decays branching to the 2.35-Mev state. From the above measurements the *K*-branch to the 0.57-Mev state may be derived. We find the *K*-branch to be 5±2 percent per disintegration. This

TABLE I. Channel settings for deriving the net *K* x-ray 0.57-Mev gamma-ray coincidence intensity.

Channel 1	Channel 2
K x-ray	0.57-Mev photopeak
K x-ray	just above 0.57-Mev photopeak
just above *K* x-ray	0.57-Mev photopeak
just above *K* x-ray	just above 0.57-Mev photopeak

result is in reasonable agreement with the 2.8 percent branch measured by Lazar and Klema.[21]

An attempt has been made to determine the lifetime of the 0.57-Mev first excited state of Pb^{207} by fast coincidence techniques. Both detectors consisted of *trans*-stilbene phosphors on RCA 5819 photomultipliers. The fast coincidence system ($2\tau \simeq 3\times10^{-9}$ sec) has been described previously.[22] Coincidences were taken between conversion electrons of the 1.06-Mev transition and a portion of the Compton distribution of the 0.57-Mev transition. An analysis of the time distribution of coincidences from the Bi^{207} source compared to that obtained from a "prompt" source taken under identical pulse-height selection conditions shows that the half-life of the 0.57-Mev state is $<4\times10^{-10}$ sec. Recently, the half-life of this state has been deduced[23] from Coulomb excitation as 1.0×10^{-10} sec.

L x-ray—1.78-Mev gamma-ray coincidences were measured in an attempt to find an observable lifetime for the 2.35-Mev state. Because of the low energy and low abundance of the *L* x-rays, it was only possible to place an upper limit of 3×10^{-8} sec on the half-life of the 2.35-Mev state.

PHOTONEUTRON EXPERIMENTS

In order to place a limit on the intensity of energetic gamma rays in the Bi^{207} decay lower than that obtained from the scintillation spectrum, photoneutron measurements have been made. The detector[24] consisted of four BF_3 counters immersed in a large box of paraffin (approximately 15 cu ft) having a central cavity into which a source could be inserted and surrounded with either Be blocks or heavy water.

With 1 mC of Bi^{207} surrounded by 9.7 kg of Be, the yield resulting from the 1.78-Mev gamma ray was 4000 counts per minute. The Be photoneutron cross section at this energy is 9×10^{-28} cm^2 according[25] to Guth and Mullin and at 2.35 Mev, the energy of the possible crossover transition, the deuterium photoneutron cross section has nearly the same value.[26] Thus the absolute detection efficiency need not be known if it is assumed that the geometries and absorption effects are the same using Be or D_2O and that the efficiency for detecting 100-kev neutrons from Be+1.78 Mev is the same as that for detecting 60-kev neutrons from D+2.35 Mev. The yields then depend only on the relative numbers of Be or D atoms present and on the relative gamma-ray intensities.

With 4 liters of D_2O surrounding the source, there was no net photoneutron yield greater than the statistical error of the background (±0.5 counts per min). If the maximum possible yield is taken to be twice the background statistical error and if the Be+1.78-Mev yield is used as a reference, then the intensity of a possible 2.35-Mev gamma ray is $<7\times10^{-4}$ of the 1.78-Mev gamma-ray intensity or $<6\times10^{-5}$ per disintegration. This figure is about 10 times lower than the limit obtained from the scintillation spectrometer measurements.

ANGULAR CORRELATION MEASUREMENTS

The gamma-gamma directional correlations of the 1.06–0.57 Mev and 1.78–0.57 Mev cascades were investigated, with the results shown in Fig. 6. For these measurements the channel windows were set to include the full-energy peaks detected by 2 in.×2 in. NaI phosphors. Similar distributions were obtained for two sources. The first source contained 50 μC of Bi^{207} and consisted of $BiSO_4$ in dilute H_2SO_4 held in a Lucite cup of 2.5-mm inside diameter and 5-mm height. The second source was 36 μC in strength and was an electroplated deposit 1 cm in diameter on a 10 mg/cm^2 Cu backing. The 1.06–0.57 Mev correlation shows a positive anisotropy of about 36 percent in agreement with the results[6] of McGowan and Campbell. The 1.78–0.57 Mev correlation is isotropic to within 5 percent.

A rough check was made on the correlation between the 1.06-Mev conversion electrons and the 0.57-Mev gamma ray by replacing one of the NaI counters with an anthracene beta detector and making runs with the electroplated source. Data taken at 180 degrees and 90 degrees indicated a positive anisotropy in excess of 30 percent, in agreement with the results[6] of McGowan.

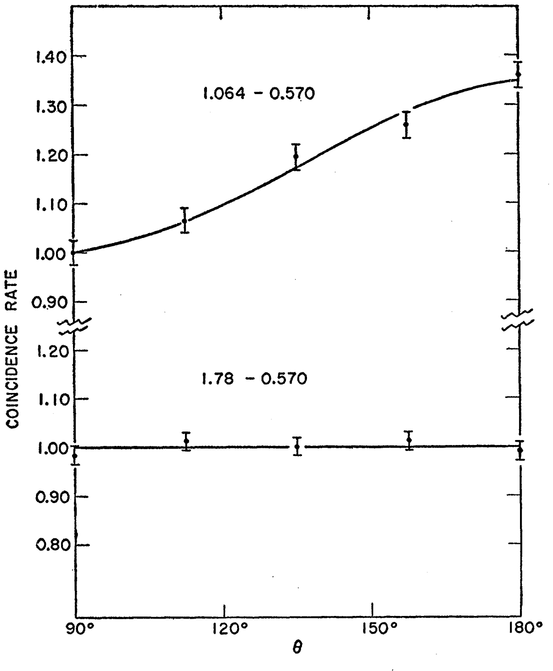

FIG. 6. Bi^{207} gamma-gamma angular correlation results.

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[23] P. H. Stelson and F. K. McGowan, Phys. Rev. **99**, 112 (1955).

[24] E. der Mateosian and M. Goldhaber, Phys. Rev. **78**, 326 (1950).

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[26] A. Wattenburg, National Research Council Preliminary Report No. 6 July, 1949 (unpublished).

DISCUSSION

All of the results presented in the foregoing are consistent with the level diagram given in Fig. 7. While many features of the Pb^{207} levels up to and including the $i_{13/2}$ state at 1.63 Mev had already been established by previous research, these experiments have shown that the 0.90- and 2.35-Mev levels are excited in Bi^{207} decay.

The state at 2.35 Mev is not likely to have a spin of $\leq 5/2$ as can be seen from the following observations:

(1) The small upper limit on the intensity of a 2.35-Mev transition to the $p_{1/2}$ ground state as found in the photoneutron experiments.

(2) The low intensity of the 1.44-Mev transition to the $p_{3/2}$ level at 0.90 Mev.

(3) The comparable intensities of electron capture branching to the states at 2.35 Mev and 0.57 Mev (spin $5/2-$) in spite of the very great difference in available energy.

The measured conversion coefficient for the 1.78-Mev transition limits the spin change involved in the transition to ≤ 2. Hence the spin of the 2.35-Mev state cannot be greater than 9/2.

Agreement of the 1.06–0.57 Mev electron-gamma angular correlation with the theoretical correlation shows that there are no disturbing effects in our sources as suggested earlier[27] resulting from the filling of electron shells following either electron capture or internal conversion. Hence the isotropy of the 1.78–0.57-Mev gamma-gamma correlation can be considered as real. If the 2.35-Mev state were $h_{9/2}$ the 1.78-Mev transition must necessarily be an $E2+M3$ transition, since a pure quadrupole transition would lead to a correlation showing a positive anisotropy of 16.7 percent. From the theoretical correlation functions[28] of Biedenharn and Rose it can be shown that for the $h_{9/2}$ assignment one can achieve approximate isotropy and at the same time satisfy the 1.78-Mev gamma-ray conversion coefficient with a mixture of $\sim$97 percent $E2+\sim$3 percent $M3$.

In the case of a 7/2 spin for the 2.35-Mev state, a mixture of $\sim$94 percent $E2$ and $\sim$6 percent $M1$ is a compatible with both the conversion and angular correlation measurements. A decision between the possible shell model assignments $f_{7/2}$ and $h_{9/2}$ to the 2.35-Mev state cannot be made from our angular correlation measurements. On the basis of more accurate correlation measurements, Lazar and Klema have assigned[21] a spin of $h_{9/2}$ to the 2.35-Mev state, with the $E2+M3$ mixture stated above for the 1.78-Mev transition.

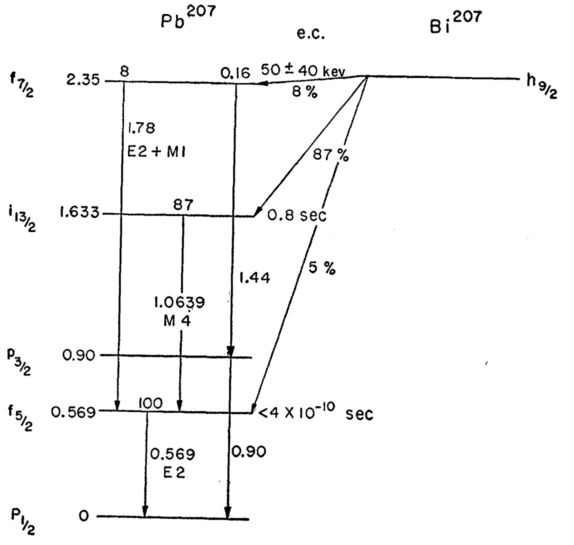

FIG. 7. Proposed decay scheme of Bi^{207}. Branching and transition intensities are adopted as being the most probable from several sets of data.

An $h_{9/2}$ assignment would mean that the 1.44-Mev transition to the second excited state at 0.90 Mev must be at least $M3$, if the latter state is assumed to be $p_{3/2}$. In this case, the 1.44-Mev K-conversion coefficient would be 2.7×10^{-2} for pure $M3$ radiation. Our value of $(5\pm 2)\times 10^{-3}$ for the K-conversion coefficient of this transition is lower than that of a pure $M3$ by a factor of 5. No $E4$ admixture can lower the K-conversion coefficient below $\sim$1 percent. We feel that this argues most strongly against an $h_{9/2}$ assignment. In the event that the K-1.44 line of Fig. 2 were actually a ghost, the real conversion coefficient would be even lower and the discrepancy with $M3$ or $M3+E4$ would be still greater. An assignment of $h_{9/2}$ to the 2.35-Mev state implies a lower limit for the lifetime of $M3$ radiation from this state, if one considers the transition within the framework of the single-particle model. Our value of 3×10^{-8} sec as the upper limit of the lifetime of the 2.35-Mev state is not by itself short enough to rule out the $h_{9/2}$ assignment.

On the other hand, an assignment of $f_{7/2}$ to the 2.35-Mev state fits all of our observations. The measured 1.44-Mev K-conversion coefficient is consistent with $E2$ radiation to the $p_{3/2}$ state. When the E^5 energy dependence is removed from the transition intensity ratio, the ratio of 1.44-Mev to 1.78-Mev $E2$ matrix elements is about 1/20 which may not be unreasonable. Prescott's observation[7] of a weak gamma ray of 1.46 Mev in coincidence with K x-rays is not compatible with the scheme proposed here since it has been found that the 2.35-Mev state is formed by L capture only. The only coincident K x-rays in this case would then arise from internal conversion of the 0.90-Mev transition and this coincidence effect would be 100 times smaller than the 1.78 K x-ray coincidence intensity.

If the 0.90-Mev gamma ray is an $M1$ transition, its K line would have an intensity 1/1500 of K-1.06 or just below the limit placed by the data. This line might become observable with a strong source and greater

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[27] D. E. Alburger and A. W. Sunyar, Phys. Rev. **98**, 276(A) (1955).

[28] L. C. Biedenharn and M. E. Rose, Revs. Modern Phys. **25**, 729 (1953).

precautions against scattering in the spectrometer and from the source backing. If the 0.90-Mev transition goes by $E2$ radiation rather than by $M1$, the K line would be less intense by another factor of 4. One could not reasonably expect to observe the 0.72-Mev transition between the $f_{7/2}$ and $i_{13/2}$ states.

In analogy with Bi^{209} it has been suggested[2] that the ground state of Bi^{207} is $h_{9/2}$. The electron capture transition to the 2.35-Mev $f_{7/2}$ level of Pb^{207} is then allowed and this could be consistent with the proposed scheme in view of the absence of K capture. Using the 8.0-year half-life for Bi^{207}, one can calculate the limiting logft values for L capture to the 2.35-Mev level, this transition having a partial half-life of about 90 years. Corresponding to the range of transition energies between the K and L binding energies, the logft value[29] lies between 5.6 and 7.8 and hence could be consistent with an allowed transition.

The presence of only L electron capture to the 2.35-Mev level leads to a value of 2.40±0.04 Mev for the total decay energy of Bi^{207}. The error implies allowable limits and the value 2.40 Mev is not necessarily the most probable decay energy. If the decay energy had been as much as 10 kev above the K-capture threshold, then the K x-ray yield in coincidence with the 2.35-Mev sum photo line would be 1/10 of the L x-ray yield according to the formula of Marshak[30] and this would have been easily observable.

Logft values may also be calculated for the main capture branch to the 1.633-Mev level and for capture to the 0.57-Mev level based on the level scheme of Fig. 7. If one uses the graphs[31] of Moszkowski, the main branch has a logft of 9.6 while the branch to the 0.57-Mev level has a logft of 11.5. These values are consistent with first and second forbidden transitions respectively as would be expected from the level assignments.

The reasonably firm assignment of $f_{7/2}$ to the 2.35-Mev level in Pb^{207} requires a reconsideration of the predicted levels in Pb^{206}. $h_{9/2}$ was assumed for the 2.35-Mev level in making these calculations. According to a private communication from M. H. L. Pryce, the only serious effect of this change is to remove the predicted 5+ level at 3124.7 kev (see Figs. 7 and 8 in reference 1), a level which was already considered as doubtful. In place of this, a 3+ level at approximately this energy is expected but it is not likely that the 739.9-kev transition or the doubtful 107.2-kev transition could be associated with it. Hence the positions of these two transitions in the Pb^{206} scheme are now uncertain. Other Pb^{206} configurations affected are numbers 11 and 12 in Table IX of reference 1 but the energies of these are so high that they are not relevant to the interpretation of the gamma-ray spectrum.

The lifetime[23] of 1.0×10^{-10} sec for the 0.57-Mev $E2$ transition is much shorter than could be expected on the single particle model for an $E2$ transition involving a neutron jump and is close to that expected for a single proton transition with unit matrix element. The transition follows the general trend[32] exhibited by $E2$'s in this region of the periodic table, most of which show a speed-up which can be interpreted in terms of collective effects.

We are indebted to J. Hudis and E. Baker for chemical preparation of the Bi^{207} electroplating solution and to J. Hudis for separation of the Y^{88} sample. We also wish to thank M. Goldhaber for helpful discussions and suggestions.

Note added in proof.—The internal conversion spectrum of Bi^{207} has been reinvestigated at 2.0 percent resolution using an intermediate-image beta spectrometer recently constructed at Brookhaven and a 15-μC source deposited on 0.5 mg/cm^2 Nylon. A line, which we believe is real, has been observed corresponding to K conversion of a 0.894±0.007 Mev transition. Its intensity is 0.0039 K electrons per 100 disintegrations (1/2100 as strong as K-1.06). The K-conversion coefficient based on this observation and on the gamma-ray measurements is $(2.4\pm1)\times10^{-2}$ suggesting $M1$ radiation (theoretical $\alpha_K=2.8\times10^{-2}$) with possible admixture of $E2$ radiation ($\alpha_K=6.9\times10^{-3}$).

The 1.44-Mev K-conversion line has been observed again and its intensity has been found to be 4.8±1 percent as strong as K-1.78 in agreement with previous measurements. The $K/(L+M)$ ratio of the 1.78-Mev transition is 4.4±0.4. Improved values for the two highest energy gamma rays are 1.43±0.01 Mev and 1.771±0.005 Mev corresponding to a most probable energy of 2.338±0.005 Mev for the Pb^{207} level.

An upper limit of 0.0015 electron per 100 disintegrations has been placed on the K-conversion line of a possible 0.324-Mev $M1$ transition between the 0.894- and 0.570-Mev states. If this transition were not l forbidden its K line might have been expected to have approximately the same intensity as K-0.894.

Upper limits of 0.002 electron per 100 disintegrations have been placed on the K-conversion lines of either a possible 0.704-Mev transition between the 2.338- and 1.634-Mev levels or a possible 0.740-Mev transition between the 1.634- and 0.894-Mev levels. If the 2.338-Mev state were $h_{9/2}$, one can calculate on the basis of single-particle estimates that a 0.704-Mev $M2$ would win out over a 1.43-Mev $M3$ by a factor of ~500. Their relative K-conversion intensities would then be in the ratio of ~2000 in favor of the 0.704-Mev line whereas our upper limit is a factor of 2. We could not rule out the $h_{9/2}$ assignment to the 2.338-Mev level from conversion intensities if the 1.43-Mev transition were predominantly $E4$. However, in that case the lifetime of the 2.338-Mev level would probably be $>10^{-4}$ sec as compared with our upper limit of 3×10^{-8} sec. These new results further confirm the $f_{7/2}$ assignment to the 2.338-Mev level.

A measurement of the half-life of Bi^{207} is now in progress by G. Harbottle of this Laboratory. Using a balanced double ion chamber standardized with radium he has obtained a preliminary value of 27±3 years for Bi^{207} based on data taken over a three-month period

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[29] The authors are indebted to Dr. M. E. Rose for making these calculations.

[30] R. E. Marshak, Phys. Rev. **61**, 431 (1942).

[31] S. A. Moszkowski, Phys. Rev. **82**, 35 (1951).

[32] A. W. Sunyar, Phys. Rev. **98**, 653 (1955).