the measured conversion line intensities of the isomeric transitions, using the theoretical conversion coefficients for the multipolarities proposed above. It should be pointed out that also the gamma-transition probabilities calculated for the isomeric transitions speak in favor of the multipolarity assignments made. However, in the case of the 1014.2-kev transition, the gamma-transition probability seems to indicate that only part of the radiation is due to the $M4$ transition.

The $E3$ assignment of the 310.5-kev transition suggests that the 703.3-kev state has spin and parity 7/2−. This is in agreement with the theoretical predictions by Pryce[7] and True.[8] Because of the $E2$ character of the 703.3-kev transition[2,4] 9/2− previously appeared more probable.

It should also be mentioned that the present results indicate that only about 65% of the feeding to the 987.6-kev level takes place via the 26.22-kev $M2$ transition.

The investigation of this isomeric decay is being continued. It is hoped that decisive information will be gained from the planned coincidence measurements. Details of experiments and results will appear in Arkiv för Fysik.

[7] M. H. L. Pryce, Nuclear Phys. **2**, 226 (1956/57).
[8] W. W. True, Princeton University (private communication).

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Isomeric Transition in Pb^{205}†

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A (26±1)-kev transition in Pb^{205} occurring in the electron capture decay of Bi^{205} has been identified from its L, M, and N internal conversion electrons measured in an intermediate-image beta-ray spectrometer. By using NaI scintillation detectors behind the source in the spectrometer the M and N lines of the 26-kev transition are found to be not in coincidence with electron-capture K x rays but they are in coincidence with a principal gamma ray of 1 Mev and weak components of ∼0.7 and ∼0.3 Mev. Since the Bi^{205} gamma rays of 987.8 and 284.2 kev and a fraction of the 703.3-kev gamma rays have been shown by Vegors and Heath to be delayed with respect to electron-capture K x rays with a half-life of 4.8 msec, the present coincidence results indicate that the delayed radiation is associated with the 26-kev transition originating from an isomeric state in Pb^{205} at 1013.8 kev. The 26-kev transition is probably a quadrupole and a possible assignment is $M2$ if the spin-parity assignment of the 987.8-kev level is 9/2− and if the 1013.8-kev level is the 13/2+ state predicted at 1.1 Mev by Pryce. The possibility that all or part of the known 1014.2-kev gamma radiation constitutes the "missing" $M4$ transition in Pb^{205} is discussed.

INTRODUCTION

OF the many gamma rays occurring in the electron-capture decay of 14.5-day Bi^{205} it had been found[1,2] that the strong 987.8-kev transition is not in coincidence with any other gamma ray in the spectrum. Vegors and Heath[3] recently extended the coincidence work and showed that this gamma ray is also not in coincidence with electron-capture K x rays, thus requiring that an isomeric state exist in Pb^{205}. It was then discovered by Vegors and Heath that an activity of 4.8-msec half-life follows the decay of Bi^{205} and that the spectrum of gamma rays in delayed coincidence with electron-capture K x rays exhibits the 987.8-kev transition and the 284.4–703.3 kev cascade transitions, the latter with a relative intensity of about 10%. They suggested that the 987.8-kev level itself may not be isomeric but that it may be fed by a highly converted low-energy transition.

In the conversion-electron spectrum of Bi^{205}, low-energy lines at about 25 kev have been reported[1,2] which have been assigned variously as the K lines of 112.2- or 115.2-kev transitions. Vegors and Heath[4] reinvestigated the low-energy region with a beta-ray spectrograph and they tentatively assigned the three most intense lines in the neighborhood of 25 kev as the L_{I}, L_{II}, and L_{III} internal conversion electrons of a 38.8-kev transition. Since this seemed to be the most likely candidate for the 4.8-msec isomeric transition the same energy region has been studied here in order to check the transition energy assignment, to see if the transition is delayed with respect to electron capture and to measure the spectrum of gamma rays in coincidence with the low-energy internal conversion lines.

EXPERIMENTAL METHODS AND RESULTS

The Bi^{205} activity was made at Oak Ridge by bombardment of radiogenic lead with 20.8-Mev protons according to the procedures described by Vegors and Heath.[3] Carrier-free separation[5] of the bismuth was carried out about 2 months after the bombardment and

† Work performed under the auspices of the U. S. Atomic Energy Commission.
[1] M. Schmorak, R. Stockendal, J. A. McDonell, I. Bergström, and T. R. Gerholm, Nuclear Phys. **2**, 193 (1956/57).
[2] A. R. Fritsch and J. M. Hollander, J. Inorg. & Nuclear Chem. **6**, 165 (1958).
[3] S. H. Vegors and R. L. Heath, Phys. Rev. **118**, 547 (1960).
[4] S. H. Vegors (private communication).
[5] D. E. Alburger and G. Friedlander, Phys. Rev. **81**, 523 (1951).

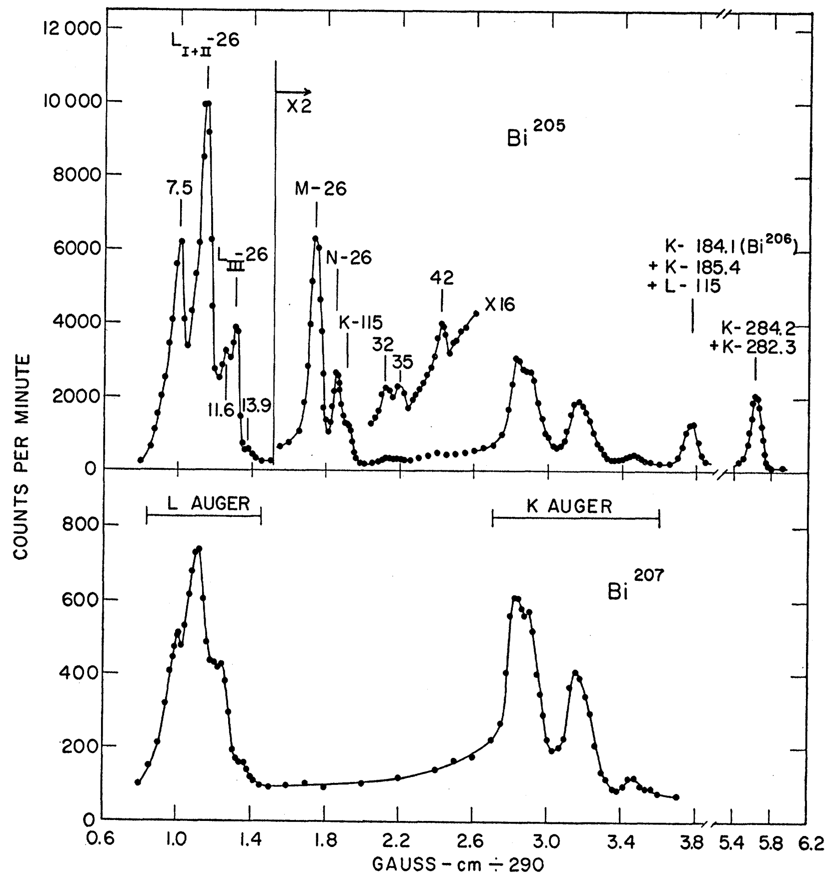

FIG. 1. Low-energy electron spectra from sources of Bi^{205} and Bi^{207} measured in the intermediate-image spectrometer using a 50 $\mu g/cm^2$ grid-supported G-M counter window.

6-mm diameter sources were prepared by electroplating onto copper backings.

A description of the intermediate-image spectrometer has been published[6] as well as some applications of the instrument to the study of low-energy electrons.[7] In the first part of the present work a G-M counter with a 50-$\mu g/cm^2$ thick grid-supported window was used for the measurement of the electron spectrum. The grid has a transmission of 77% and the counter was filled with a mixture of 1 cm of argon and 1 cm of ethyl alcohol vapor. The upper part of Fig. 1 shows the Bi^{205} electron spectrum between 5 and 100 kev together with the unresolved K-284.2$-K$-282.3 line included as an intensity reference. A spectrometer linewidth setting of 2.3% was used for these measurements. The intensity of the line labeled K-184.1$+K$-185.4$+L$-115 shows, by comparing with previous results[8] on Bi^{206}, that the relative amount of Bi^{206} present is at most a few percent of the total activity. Because of small systematic differences between the energies of the lines below 60 kev derived from Fig. 1 and previous determinations,[1,2] which may be the result of stray magnetic field effects, the accuracies of the energies of all of these lines is probably no better than ± 1 kev.

For comparison purposes the Auger electron spectrum from a 6-mm diameter Bi^{207} source, taken under the same conditions, is shown in the lower part of Fig. 1. This source is considerably thicker than the Bi^{205} sample as may be seen from the L-Auger region.

Electron-gamma coincidence measurements were carried out by replacing the thin-window counter with an anthracene detector consisting of a crystal $\frac{1}{8}$ in. thick by 1-in. diameter cemented on the end of a 28-in. long, 2-in. diameter light pipe curved down to 1-in. diameter at the crystal end. An RCA-6342 photomultiplier tube was cemented onto the opposite end of the light pipe and it was magnetically shielded. Considerable reduction in tube noise was achieved by cooling the photomultiplier tube with dry ice. Under the pulse-height bias conditions selected, the ~60-kev (K-2L) Auger line could be detected with >90% efficiency whereas the efficiency for detecting the 22-kev line (M-26 in Fig. 1) was 12% and nothing at all above noise could be seen in the L-Auger region. The efficiency for detecting the M-26 line was sufficient for obtaining good coincidence data. At a distance of 2 cm behind the spec-

[6] D. E. Alburger, Rev. Sci. Instr. **27**, 991 (1956).
[7] G. Scharff-Goldhaber, D. E. Alburger, G. Harbottle, and M. McKeown, Phys. Rev. **111**, 913 (1958).
[8] D. E. Alburger and M. H. L. Pryce, Phys. Rev. **95**, 1482 (1954).

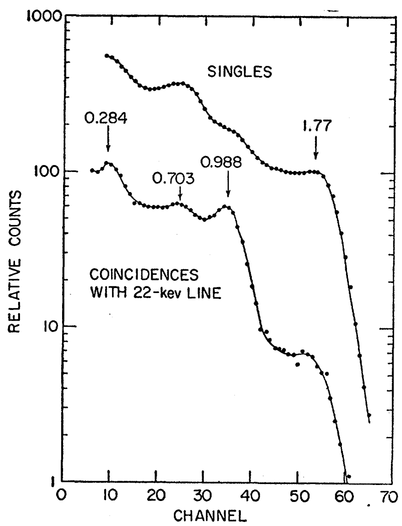

FIG. 2. Upper curve—singles gamma-ray spectrum of Bi^{205} recorded with a 2 in.×2 in. NaI crystal on the end of a 28-in. long light pipe. Lower curve—gamma-ray spectrum in coincidence when the spectrometer was focused on the 22-kev line (M-26 in Fig. 1), using an anthracene crystal detector. Gamma-ray energies have been taken from previous work.

trometer source was located a 2 in.×2 in. NaI crystal on the end of a 28-in. light pipe leading out to another magnetically shielded 6342 phototube. Standard coincidence circuitry (resolving time$=2\times10^{-7}$ sec) and a 100-channel pulse-height analyzer were used. Coincidence runs were taken at the maximum spectrometer transmission.

Some of the results of the coincidence work are shown in Fig. 2. Owing to the losses in the light pipe, the gamma-ray resolution of the detecting system is rather poor. However, the singles curve exhibits structure which may be correlated with the spectrum taken with good resolution (see reference 3, Fig. 1). When the spectrometer was focused at the peak of the 22-kev electron line (labelled M-26 in Fig. 1) the gamma-ray spectrum obtained in coincidence in a 2-hour run is shown in the lower part of Fig. 2. Between channels 30 and 40 the real-to-random ratio was 7 and above channel 45 the yield is due to random coincidences. The coincidence curve displays a principal peak at 1 Mev and weak lines at ~0.3 and ~0.7 Mev. A very similar spectrum was obtained in coincidence with the 25-kev line (N-26 in Fig. 1) whereas the spectrum in coincidence with the K-$2L$ Auger line (the lowest energy and most intense K-Auger line in Fig. 1) had about the same shape as the singles curve in Fig. 2.

As a test to see if the 26-kev transition itself is delayed the low-energy electron spectrum was measured in coincidence with K x rays. For these experiments the 2 in.×2 in. NaI crystal was replaced with a NaI crystal 2 mm thick and 2×2 cm^2 in area, a size which greatly diminishes the detection of higher energy radiations as compared with the detection of K x rays. With a channel placed around the K x ray peak the spectra of low-energy electrons in prompt and in random coincidence with the K x rays were run. In the difference curve of net coincidences the K-115 line amplitude was found to be ~4 times larger than the M-26 line, whereas in singles (see Fig. 1) the K-115 line is estimated to be 1/7 as intense as the M-26 line. Thus there are relatively only ~5% as many K x rays in coincidence with the M-26 line as there are in coincidence with the K-115 line.

DISCUSSION

There are three arguments which support the energy assignment of 26 kev to the low-energy transition in Pb^{205}. If the lines in Fig. 1 labelled M-26 and N-26 were instead the L_{I+II} and L_{III} lines of a 38.8-kev transition, as tentatively proposed by Vegors and Heath, (the energy separation N-M is very nearly the same as $L_{III}-L_{I+II}$), the corresponding M and N lines would then appear in the vicinity of the weak lines at 32 and 35 kev in Fig. 1. However, the intensity ratio of the sum of the 22- and 25-kev lines to either the 32- or 35-kev line is ~60 which is at least an order of magnitude larger than the theoretical L/M ratio for a 38.8-kev transition of any multipole order according to calculated internal conversion coefficients.[9] Since the 22- and 25-kev lines have the proper energy separation for M and N lines and since both display the same gamma-ray spectrum in coincidence, the logical assignment is that they are in fact the M and N lines of a 26-kev transition. It is possible that the lines assigned by Vegors and Heath as L_I and L_{II} of a 38.8-kev transition are actually the M subshell lines of the 26-kev transition.

A second argument is based on transition intensity considerations. The sum of the intensities of the 22- and 25-kev lines, suitably corrected for their widths, was compared with the K-703.3 line intensity. By making use of the known data on the relative intensities of the more energetic internal conversion lines in the Bi^{205} spectrum, which have been measured several times with great care, together with the K-shell internal conversion coefficient[10] of the 987.8-kev transition, the ratio of the sum of the 22- and 25-kev line intensities to the total *transition* intensity from the 987.8-kev state was calculated to be approximately 1/3. No gamma rays of >10 kev have been seen[3] in coincidence with the 987.8-kev gamma ray which means that the low-energy isomeric transition must be highly converted. It may be concluded that other internal conversion lines must also be in coincidence with the 987.8-kev gamma ray in order to account for the transition intensity from this state and this would be explained if the 22- and 25-kev lines were the M and N lines of a 26-kev transition, the L lines being at a lower energy. According to these measurements the $L/(M+N)$ ratio is ~2.

[9] M. E. Rose *Internal Conversion Coefficients* (Interscience Publishers, Inc., New York, 1958).
[10] R. Stockendal and S. Hultberg, Arkiv Fysik **15**, 33 (1959).

Finally, it is fairly convincing from a comparison of the two curves of Fig. 1 that the L_{I+II} and L_{III} lines of a 26-kev transition in Pb^{205} have actually been observed. In spite of the source thickness effects which are obviously present in the Bi^{207} L-Auger region, three of the four peaks may be correlated in momentum position with the peaks labeled 7.5, 11.6, and 13.9 kev in the Bi^{205} spectrum. The largest Bi^{205} peak on the other hand is definitely at a higher momentum value than the largest Bi^{207} L-Auger peak. Furthermore, the Bi^{205} peak labeled L_{III}-26, which has a measured energy of 12.6 kev, has no counterpart in the Bi^{207} spectrum. Its energy is correct to be an L_{III}-26 line while the energy of the most intense line (9.6 kev) agrees approximately with that of an L_{I+II}-26 line. Because of the superposition of the L-26 conversion lines on the L-Auger lines, it has not been possible to show whether the L_{I+II} line is predominately L_I or L_{II}, or to derive accurate L_{I+II}/L_{III} or L/M intensity ratios. Judging from the appearance of the spectrum, it is likely that the L_{I+II}/L_{III} ratio lies between 1 and 2. One may also note from a comparison of the two curves in Fig. 1 that the total intensity of electrons in the L-Auger region of Bi^{205} is much greater relative to the K-Auger lines than in the case of Bi^{207}. (Note the factor of 2 change in the ordinate scale in the Bi^{205} curve.)

The assignment of the 26-kev transition as belonging to the 4.8-msec isomer is based on the two sets of coincidence data. Firstly, it has been shown that the M-26 line is only weakly in coincidence with K x rays. A small coincidence effect is expected to occur because of K-shell internal conversion of the 284.2-kev transition but even disregarding this contribution the coincidence yield of the M-26 line with K x rays is more than a factor of 10 weaker than it would be if the 26-kev transition were in prompt coincidence with the K-electron capture decay of Bi^{205}. The other coincidence data have shown that the spectrum of gamma rays in prompt coincidence with the M-26 and N-26 conversion lines is similar to the spectrum of gamma rays which are delayed with a half-life of 4.8 msec, as found by Vegors and Heath.

These results indicate that the 4.8-msec isomeric state in Pb^{205} is at an energy of 1013.8 kev if, as is generally accepted, the 987.8-kev gamma ray is a ground-state transition. Based on the single-particle lifetime formulas it is probable that the 26-kev transition is a quadrupole. Whether it is electric or magnetic cannot be established from the present rather inaccurate estimates of the L_{I+II}/L_{III} and L/M ratios. There is a possibility that the 1013.8-kev level corresponds to the $13/2+$ state predicted by Pryce[11] to lie at 1.1 Mev and by True[12] to lie at 1050 kev above the ground state of Pb^{205}. If this were the case the 26-kev transition would be an $M2$ if the 987.8-kev state is $9/2-$.

[11] M. H. L. Pryce, Nuclear Phys. **2**, 226 (1956/57).
[12] W. W. True, see reference 3.

The existence of an energy level at 1013.8 kev at once leads to the question as to whether or not all or part of the known 1014.2-kev transition in Pb^{205} constitutes a direct ground-state transition from the 1013.8-kev level, since the energies agree within the limits of error. (If the L_{III}-38.8 line measured by Vegors and Heath is reassigned as an N line, the transition energy would be close to 26.5 kev, depending on what value is used for the N-shell binding energy. Adding this transition energy to the 987.8-kev level gives 1014.3 kev as the energy of the isomeric state, which is in remarkable agreement with the energy of the known 1014.2-kev transition.) Apparently neither the K-conversion coefficient nor the K/L ratio of the 1014.2-kev transition has been measured and the only information[10] on its multipolarity is that it is not $E1$. Although this transition has already been assigned as part of a (1014.2-1552.0)-kev cascade from a level at 2566.5 kev, whose ground-state transition has been observed,[10] let us assume for the moment that the 1013.8-kev level is $13/2+$ and that the 1014.2-kev transition actually takes place between this level and the $5/2-$ ground state. The branching ratio relative to the 26-kev transition may be calculated readily by making use of the K-1014.2 line intensity relative to the K-987.8 line intensity, the theoretical K-conversion coefficient of a 1014.2-kev $M4$ transition together with the known K-conversion coefficient of the 987.8-kev transition and the relative branching of this state. The result is that the 1014.2-kev gamma-ray branch would be 0.8% relative to the 26-kev transition. Since the half-life of the 1013.8-kev state is 4.8 msec the partial half-life for the emission of 1014.2-kev gamma radiation would be about 0.6 sec.

According to the systematics[13] of isomeric transitions in odd-mass lead isotopes, based on the occurrence of $M4$ transitions in Pb^{197}, Pb^{199}, Pb^{201}, Pb^{203}, and Pb^{207} an $M4$ transition of 980 ± 40 kev energy and 1.5 ± 0.5 sec half-life is expected to occur in Pb^{205}. It is, therefore, conceivable that the 1014.2-kev gamma ray, both because of its energy and its tentatively derived partial half-life, may indeed be the "missing" $M4$ transition.

On the other hand, Vegors and Heath find[4] coincidences between the 1552.0- and 1014.2-kev gamma rays. It would appear that there actually may be two 1014.2-kev transitions, one of which is part of a cascade from the 2566.5-kev state and the other of which is an $M4$ ground-state transition.

In order to clarify this situation the following experiments are suggested:

(a) Measure the K/L ratio and/or the K-conversion coefficient 1014.2-kev transition in order to establish its multipolarity.

(b) Look for structure in the K-1014.2 line.

(c) See if the 1014.2-kev transition is delayed with respect to electron capture K x rays.

[13] R. Stockendal, J. A. McDonnell, M. Schmorak, and I. Bergström, Arkiv Fysik **11**, 165 (1956).

Tests (a) and (b) require high-resolution beta-ray spectrometer techniques. A coincidence spectrometer having an electron-line resolution of 1% or better might possibly provide an answer to (c). (An attempt to do this was made with the intermediate-image spectrometer without success.) The problem is difficult because the 1014.2-kev transition is bracketed between the 987.8- and 1043.7-kev transitions both of which have K-conversion lines $\sim$5 times as strong as the K-1014.2 line and which are separated from the K-1014.2 line by $\sim$2% in momentum. If the approach is to look for the absence of coincidences between the K-1014.2 line and the K x rays due to electron capture, one must bear in mind that K-conversion lines are always in coincidence with their own corresponding K x rays. In the coincidence spectrum of K-conversion lines with K x rays the intensity ratio of the K-1014.2 line to the K-1043.7 line should be measurably smaller than the ratio in the singles electron spectrum if the 1014.2-kev transition is delayed. The reduction of the ratio K-987.8/K-1043.7 may be taken as a measure of what to expect since the 987.8-kev transition is known to be delayed. It might be more profitable to look for the complete absence of coincidences between K x rays and the L-1014.2 line. An experiment to see if the K-1014.2 line is in delayed coincidence with K x rays would probably be very difficult.

Under the assumptions discussed above, a partial half-life value of 0.6 sec for the 1014.2-kev transition would be a lower limit. Any contribution to its K line by the K line of the above-mentioned cascade transition from the 2566.5-kev state would lower the $M4$ branch relative to the 26-kev transition and would thereby increase the derived partial half-life of the $M4$ transition in the direction of the value suggested by the systematics. On the other hand if the 1013.8-kev level proves to be a 13/2+ state at least 1/3 of the K-1014.2 line intensity would have to correspond to the $M4$ transition in order for the partial half-life to agree with the systematics.

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Proton-Proton Scattering at 25 Mev*

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The differential cross section for proton-proton scattering has been measured for 23 center-of-mass angles from 10° to 90°, with ±0.8% absolute probable error at angles greater than 14°. The incident proton energy was 25.63-Mev lab. The 90° cross section is 18.59 millibarns, and the interference minimum of 17.09 mb occurs at 24° c.m. A set of phase shifts which fit the data are: $^1S_0$, 49.5°; $^3P_0$, 8.2°; $^3P_1$, −4.2°; $^3P_2$, 2.0°; $^1D_2$, 0.62°.

METHOD

THE scattering chamber and electronics and most of the experimental techniques used in this experiment were similar to those reported in a 40-Mev proton-proton scattering paper[1] from this laboratory.

The proton beam was obtained from the second accelerating cavity of the Minnesota linear accelerator. Since the desired energy was intermediate between the terminal energies of the cavity (10 and 40 Mev), a sheet copper diaphragm was placed in the cavity between two drift tubes at such a position that the electric field was cut off in the "later" part of the cavity. This gave a beam of normal intensity, angular divergence, and energy spread (±0.5%). The mean energy and energy spread were measured by a magnetic spectrometer.[1]

The target material was hydrogen gas at ½ atmosphere pressure, obtained from a palladium filter. To avoid substantial contamination of the gas by foreign gases from the chamber walls, fresh gas was added continuously at the rate of about one chamberful per hour, while the old gas was bled out through a pressure-regulating valve, as described in a recent publication.[2]

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† Now at Midwestern Universities Research Association, Madison, Wisconsin.
[1] L. H. Johnston and D. A. Swenson, Phys. Rev. **111**, 212 (1958).
[2] L. H. Johnston and D. E. Young, Phys. Rev. **116**, 989 (1959).