It also compares well with an earlier microwave determination by Geschwind and Gunther-Mohr.[8]

$$\frac{M(30)-M(29)}{M(30)-M(28)}=0.49941\pm 0.00005.$$

ACKNOWLEDGMENT

We are very grateful to Drs. Børge Bak and John Anderson of the University of Copenhagen for furnishing us the SiD_3F used in this investigation.

[8] S. Geschwind and G. R. Gunther-Mohr, Phys. Rev. **81**, 882 (1951).

PHYSICAL REVIEW VOLUME 92, NUMBER 5 DECEMBER 1, 1953

The Isomeric Transition of Pb^{207} as an Energy Standard in Beta Spectroscopy

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(Received August 24, 1953)

The K-conversion line of the 1.06-Mev isomeric transition following the electron-capture decay of Bi^{207} is suggested as a useful energy standard for beta-spectroscopy. While the 50-year half-life and 10 percent conversion coefficient are comparable to Cs^{137}, the 60 percent higher energy, larger percentage K to L momentum separation, and the possibility of making thin and more uniform sources may be advantageous. Precision measurements have been carried out in a double-focusing spectrometer by comparison with the 1.02-Mev electrons of RaC. The Pb^{207} K-line has a momentum of 4657.9 ± 1.0 gauss-cm from which an electron energy of 975.9 ± 0.3 kev and a transition energy of 1063.9 ± 0.3 kev are derived. Measurements have also been made on the K/L and $K/(L+M)$ ratios, which are 3.95 ± 0.25 and 3.00 ± 0.25 respectively. When compared with data on other $M4$ transitions, these results indicate that deviations from the empirical K/L curves take place at high Z. The usefulness of Bi^{207} as a test source for beta-gamma coincidence detectors is discussed.

INTRODUCTION

ABOVE 0.5 Mev the only generally useful internal-conversion reference standards which have been measured[1] up to the present with an accuracy of ~ 2 parts in 10^4 are the 3381.3 gauss-cm line of Cs^{137} and the 9986.7 gauss-cm line of ThX. Although the 1.33-Mev gamma ray of Co^{60} and two electron lines of RaC at 1.02 and 1.32 Mev have now been determined[2] within this accuracy, the Co conversion electrons are impractical to use because of low-conversion coefficient, small K to L separation, and poor specific activity, while the RaC has the difficulties of a 20-min half-life and a large beta-ray continuum under the lines.

Bi^{207} offers the possibility of partially filling in the wide gap between Cs^{137} and ThX, insofar as electron lines are concerned. This isotope, which decays by electron capture to Pb^{207}, was first reported[3] by Neumann and Perlman. They estimated the half-life as being approximately 50 years, and they found a number of internal-conversion lines which they measured in a shaped magnetic field beta-ray spectrometer at 1.5 percent resolution. By far the strongest line occurs at 975 kev, corresponding to a transition energy of 1063 kev. A 0.9-sec isomeric activity in lead, observed[4] somewhat earlier by Campbell and Goodrich, was interpreted[5] by Goldhaber and Sunyar as belonging to the 1.06-Mev gamma ray of Pb^{207}, which they then assigned as an $M4$ transition. Relative conversion coefficients of the 1.06- and 0.56-Mev gammas, derived by Grace and Prescott[6] and by Wapstra,[7] supported this assignment. Recently Friedlander *et al.* have shown[8] conclusively that the 0.9-sec activity belongs to Pb^{207}.

Although the decay scheme of Bi^{207} is not yet established, it is probable that the isomeric transition occurs in a fairly large percentage of the decays. The theoretical K-shell conversion coefficient of the isomer is 0.103, and one can expect a yield of conversion electrons quite comparable to that from a similar source strength of Cs^{137}. Because there is no electron continuum and the other lines in the Bi^{207} spectrum are relatively low in intensity and widely separated, the K-1064 line can be used with virtually no scattered background effects.

Aside from extending the energy range of electron reference lines by approximately 60 percent above Cs^{137}, the bismuth activity has several advantages over the latter. One of these is the larger percentage momentum separation between K and L lines resulting from the higher atomic number. In the case of cesium the K to L separation amounts to 3.5 percent in momentum. When

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[1] Lindström, Siegbahn, and Wapstra, Proc. Phys. Soc. (London) **B66**, 54 (1953).

[2] Lindström, Hedgran, and Alburger, Phys. Rev. **89**, 1303 (1953).

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

[4] C. Campbell and M. Goodrich, Phys. Rev. **78**, 640 (1950).

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

[6] M. A. Grace and J. R. Prescott, Phys. Rev. **84**, 1059 (1951).

[7] A. H. Wapstra, thesis, Amsterdam, 1953 (unpublished).

[8] Friedlander, Wilson, Ghiorso, and Perlman, Phys. Rev. **91**, 498 (1953).

working at a spectrometer resolution no better than 2.5 percent, it is not possible for calibration purposes to establish the extrapolated high-energy edge of the K line with an accuracy which could be expected if the L-conversion electrons did not interfere. Bi^{207}, on the other hand, has a K to L separation of 5.5 percent in momentum, or 1.6 times that of Cs^{137}. Thus at 3 percent resolution there will still not be any calibration difficulties because of the L electrons.

Another advantage results from the ease with which thin and very uniform sources of Bi^{207} can be prepared by carrier-free chemistry and electroplating techniques. In part of this work measurements have been made at a resolution of 0.23 percent with no perceptible energy-spread of the 976-kev line as a result of source thickness.

Conversion electron intensity ratios of this transition are of interest for comparison with the improved empirical curve of $K/(L+M)$ ratios for $M4$ transitions published[9] by Graves, Langer, and Moffat. Experimental $K/(L+M)$ values of the Pb^{207} isomer have been reported as 4.6 by Neumann and Perlman[3] and 3.4 by Wapstra,[7] These results differ widely from each other, and neither falls as close to the curve of Graves *et al.* as one would like unless the unstated experimental errors are large or there exist deviations at high Z. In Wapstra's measurements the K- and L-lines were barely resolved, and the intensity ratio was obtained by a certain amount of curve analysis.

EXPERIMENTAL PROCEDURE AND RESULTS

The Bi^{207} sources, prepared originally in connection with an investigation of Bi^{206} decay, were made by bombarding lead targets in the large cyclotron with 25-Mev deuterons for 100–200 microampere-hours. After allowing several days for 12-hour Bi^{204} to decay, separations of bismuth were carried out by Dr. W. Forsling and Mr. T. Karlsson according to the chemical procedures described[10] earlier. Final energy measurements were made on the Bi^{207} line with a 2 mm$\times$14 mm sample which had been electroplated on a copper-foil backing at a potential of 3 volts for 30 minutes. Conversion intensities were studied with a larger and somewhat stronger source estimated to contain approximately 1 microcurie of Bi^{207}.

The 1.02-Mev electron line of RaC mentioned earlier is a very convenient reference standard since its momentum, which has been measured[2] absolutely as 4839.8$\pm$0.8 gauss-cm, lies only 3.8 percent higher than the Bi^{207} K line. In this energy region the nonlinearity of the spectrometer has proved[2] to be not more than 1 part in 10^4 per 10 percent change of momentum. Thus any effect of nonlinearity in these experiments is expected to be small compared with other errors. Strong sources of RaC were made by electrostatic collection on copper strips using 75–400 mC ampules of radon in a special radon chamber designed by Professor H. Slätis.

Comparisons of Bi^{207} and RaC were carried out in the 50-cm radius double-focusing spectrometer at a resolution of 0.23 percent by determining the extrapolated high-energy edges of the K lines. The sources were attached to a holder which has a 2-mm wide slit and whose position in the spectrometer can be reproduced accurately. In the RaC runs, a monitoring technique corrected for source decay. The average of four comparison measurements which agreed with each other to within 1 part in 10^4 gives the ratio of Bi^{207}:RaC momenta as 0.96241$\pm$0.00017. From this figure a momentum of 4657.9$\pm$1.0 gauss-cm can be derived for Bi^{207} based on the absolute value of RaC. The corresponding Bi^{207} electron energy is 975.9$\pm$0.3 kev and the transition energy, found by adding the 88.0-kev binding energy[11] of lead, is 1063.9$\pm$0.3 kev.

In one of the runs a check was made by determining the extrapolated edge of the Cs^{137} line. The spectrometer calibration constant obtained in this measurement differed by 3.7 parts in 10^4 from that derived from RaC. This is just at the limit of the combined probable errors of the two absolute values and cannot be interpreted as establishing a definite nonlinearity of the spectrometer as great as 1:10^4 per 10 percent momentum change.

A study of the relative conversion intensities of the 1.06-Mev transition was made at a spectrometer resolution of 0.40 percent where the L and M electrons are completely separated. From measurements of the shapes and amplitudes of the lines the following ratios are derived: $K/L=3.95\pm0.25$ and $K/(L+M)=3.00\pm0.25$. The L line has a width and shape closely similar to the K line, and it is easily shown at this resolution that it corresponds in energy to L_{I} and/or L_{II} electrons. There is no suggestion that L_{III} electrons are present. In any case their intensity is not more than 15 percent of the total L conversion.

Recent work[12] of Prescott has indicated that a hitherto undetected or unresolved "prompt" transition of about 1.0-Mev may be present in Bi^{207} decay. A careful search was made over the gamma-energy range 1064 kev$\pm$25 percent both at 0.75 and 0.4 percent resolution for the K-conversion electrons associated with such a transition. An upper limit of 1.5 percent intensity relative to K-1064 can be placed on the existence of such a line unless it falls on one of the 1064-kev conversion lines.

DISCUSSION

Counting rates at the peak of the K-1064 line varied from 500 per minute at 0.75-percent resolution down to 40 per minute at 0.23-percent resolution. While these intensities are admittedly very low for use as calibration

[9] Graves, Langer, and Moffat, Phys. Rev. **88**, 344 (1952).
[10] D. E. Alburger and G. Friedlander, Phys. Rev. **81**, 523 (1951).
[11] Hill, Church, and Mihelich, Rev. Sci. Instr. **23**, 523 (1952).
[12] J. R. Prescott, thesis, Oxford, 1953 (unpublished).

standards, it may be pointed out that the chemical separations were made at a time when more than half of the active bismuth atoms consisted of Bi^{205} and Bi^{206} and furthermore no attention was paid to the amount of Bi^{207} in the samples. The experiments described here were performed 6 months after bombardment, by which time the Bi^{207} was essentially the only activity remaining. When the original plating solution was counted, it was found that less than one-third of the total activity had been removed in preparing the samples. From the standpoint of Bi^{207} calibration sources, it would be more favorable to make a long deuteron bombardment of lead, i.e., at least 1000 microampere-hours, and then to allow several months to elapse before doing chemistry on the target. With careful chemistry very high specific activities of Bi^{207} can be expected since, in the carrier-free state, one microcurie of Bi^{207} corresponds to a mass of 3×10^{-5} mg. Sources of 1 to 10 microcurie per mm^2 should be adequate for most purposes, and even if a small amount of bismuth carrier is added during the separation, the source thickness should not be appreciable.

The K-565 conversion line of Bi^{207}, whose intensity according to Neumann and Perlman is lower than K-1064 by a factor of 5, might also make a useful calibration standard. The sources now available here are too weak to carry out precision determinations on this line.

Cross-section functions for the production of various bismuth-isotopes are not known at present. However, it has been observed by study of the conversion electron lines that the ratio of Bi^{207} to Bi^{206} produced by thick lead target bombardment with deuterons at 25 Mev is several times as great as it is at 16 Mev. At the same time the 14-day lines of Bi^{205} are extremely weak in the sources made at the lower energy, which indicates that this isotope is probably formed by the $Pb^{206}(d,3n)Bi^{205}$ reaction whose threshold must be in the neighborhood of 16 Mev. Although the yield of Bi^{207} at 16 Mev is considerably lower than it is at 25 Mev, there is an advantage in that the waiting period which must be allowed for decay of shorter-lived activities depends mainly on 6-day Bi^{206} and not on 14-day Bi^{205}.

The $K/(L+M)$ ratio of 3.00 ± 0.25 obtained in the present work is lower than the value 4.0 from the curve of Graves *et al.* by considerably more than the error. This is not the first time that deviations from the empirical curves at high Z and high energy have been observed. Another case is that of Pb^{206}, whose first excited state at 803 kev results in $E2$ radiation giving[10] a $K/(L+M)$ ratio of 3.7. Later and more accurate measurements[13] on Po^{210} and Bi^{206} have yielded the values 3.8 and 4.0 respectively for this transition. The ratio according to the curve of Goldhaber and Sunyar, extended[14] to lower Z^2/E, should be greater than 6 for electric quadrupole radiation. The results on Bi^{207} presented here give further evidence that deviations from the empirical curves occur for energetic transitions in high-Z elements. Both of the transitions considered above have $K/(L+M)$ ratios which are approximately 30 percent lower than the empirical curves. In such cases the assignments of multipole orders based on conversion ratios should be made with some degree of caution.

Since the 1.06- and 0.565-Mev transitions of Pb^{207} have been shown[6] to be in cascade and to be approximately equal in intensity, Bi^{207} can be expected to be useful for testing the over-all efficiency of beta-gamma coincidence arrangements. Application can be made either to simple counters or to coincidence spectrometers such as a magnetic lens for electrons in conjunction with a gamma scintillation detector. The 10-percent K-conversion coefficient of the 1.06-Mev transition together with the reasonably high efficiency for detecting the gammas in a crystal allows a good yield of coincidences between the conversion electrons and the 565-kev gammas to be observed. Dr. S. Thulin of this laboratory has recently used Bi^{207} samples electroplated on 2.5 mg/cm^2 copper backings for such purposes in the Slätis-Siegbahn intermediate-image spectrometer modified with a NaI gamma detector near the source.

ACKNOWLEDGMENTS

The author is indebted to Dr. A. Hedgran for helpful discussions of precision techniques. Cyclotron bombardments were kindly performed under the direction of Dr. H. Atterling, and chemical separations of the activity were carried out by Dr. W. Forsling and Mr. T. Karlsson. The author would like to thank Professors Manne Siegbahn and Kai Siegbahn for the generous hospitality of the Nobel Institute during 1952–53.

[13] D. E. Alburger (unpublished values).
[14] D. E. Alburger, Phys. Rev. **88**, 339 (1952).