dependence than is observed. This conclusion still holds when the values of I are taken from proton data, instead of being assumed proportional to Z, and when corrections for the density effect are included. The same remarks apply with less force to the comparison of Ne^{19} positrons in lead and brass, since the logarithmic dependence of the stopping power would alone be sufficient to produce a lead-to-brass ratio of 1.17 (1.13 with the corrections of Table III), whereas the experimental ratio of 1.15 could be attributed entirely to the effects of bremsstrahlung and single-quantum annihilation.

If the conclusion is accepted that bremsstrahlung has been considerably overestimated in the calculations, it must also be recognized that a 50 percent reduction in the bremsstrahlung cross section would make the calculated pulse-height distributions for A^{35} positrons in lead and brass smaller than the experimental ones by factors of 0.5 to 0.7. This discrepancy would then be similar for A^{35} positrons in all three stopping materials, but would not be shared by the lower-energy positrons of Ne^{19} and C^{11}.

In summary, the experimental results support the γ-ray energy dependence of the two-quantum annihilation cross section and, in some cases, but not in others, the magnitude of the cross section. The agreement is satisfactory for Ne^{19} positrons stopping in brass or lead and for C^{11} positrons, but not for Ne^{19} positrons in Lucite. The disagreement for the higher-energy A^{35} positrons is large and has no apparent explanation, unless it is due to an inadequacy in the cross section in this energy region.

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A Precise Momentum Measurement of the *F* Line of Thorium B*†

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The momentum of the internal conversion electrons of the *F* line of thorium B has been compared with the momentum of electrons accelerated through a known potential difference. The comparison was made by means of an iron-free high-resolution solenoidal magnetic field beta-ray spectrometer. The value obtained for the *F* line is 1388.56±0.21 gauss-cm. Other useful calibration lines following the decay of thorium B have also been measured by comparison with the *F* line.

INTRODUCTION

UNTIL recently the most accurately known beta-ray momentum standard was Siegbahn's[1] measurement of the *F* internal conversion line in thorium B. The interest in precision beta- and gamma-ray spectroscopy received considerable stimulation by the accurate curved-crystal spectrometer wavelength determinations of nuclear gamma rays and annihilation radiation by DuMond and others.[2,3] The initial objectives of the present work[4] were to improve existing standards, and to endeavor to resolve an apparent inconsistency between the calculated and measured energy of annihilation radiation.[5] DuMond[6] pointed out that the discrepancy had been noted in earlier determinations[3] of the energy of annihilation radiation, and that it could be accounted for by an electron-positron mass difference of ~250 ev.

While the experiment discussed in this paper was in progress, several other careful energy measurements were reported. Lindström[7] determined the momentum of the *F*, *I*, and *L* internal conversion lines of thorium by a direct measurement of the deflecting magnetic field (in terms of the proton magnetic moment) and of the radius of curvature of the electron trajectories. A determination of the momentum of the *A*, *F*, and *I* lines by a different method was made by Craig.[8] In addition, other standard conversion lines and gamma rays have been measured with considerable accuracy.[9,10]

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[5] A. Hedgran and D. A. Lind, Phys. Rev. **82**, 126 (1951).

[6] J. W. M. DuMond, Phys. Rev. **81**, 468 (1951).

[7] G. Lindström, Phys. Rev. **83**, 465 (1951); Arkiv Fysik **4**, 1 (1951).

[8] H. Craig, Phys. Rev. **85**, 688 (1952).

[9] Muller, Hoyt, Klein, and DuMond, Phys. Rev. **88**, 775 (1952).

[10] W. L. Brown, Phys. Rev. **83**, 271 (1951); G. Lindström, Phys. Rev. **87**, 678 (1952); K. Siegbahn, Physica **18**, 1043 (1952).

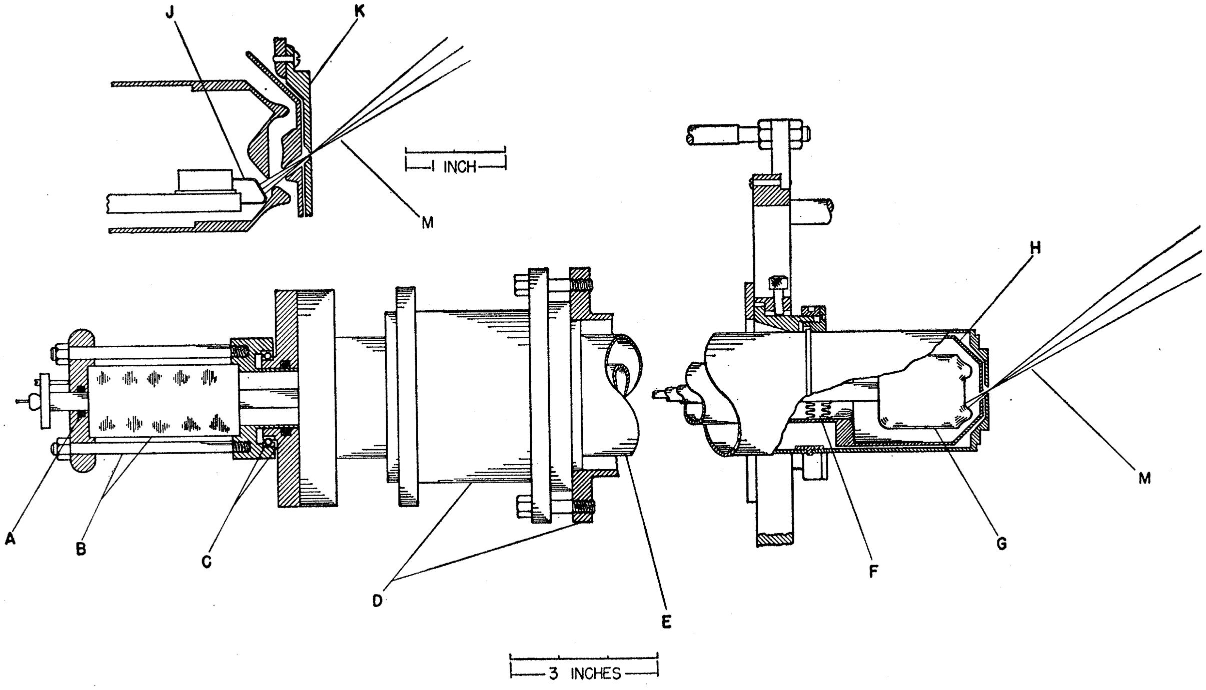

FIG. 1. The electron gun. The unit fits inside the tube (E) which is inserted into the spectrometer through a sliding seal and vacuum gate (D). The insulated electrode (G) is supported by the insulators (F) and (B). The insulated structure and the grounded shield (H) rotate as a unit by means of the vacuum seal and ball bearings (C). In addition, the electrode (G) and the filament (J) can be adjusted to provide a uniform electron beam (M) at the correct angle with respect to the spectrometer axis. The details of the accelerating electrodes are shown in the inset. The effective electron source is provided by an 0.014-inch hole in the disk (K). The thorium B source mounted on the structure in place of the disk (K).

The early inconsistency between the crystal spectrometer values for the annihilation radiation and the calculated value assuming equal positron-electron masses has been resolved.[11] Further, a direct comparison of m/e for the positron and for the electron has shown the masses to be equal to within about 100 ev.[12]

In view of these latter developments our method of precision momentum measurement was not pursued beyond a limited objective: viz., to provide an independent determination of one calibration standard, the thorium B F line. We have compared the momentum of these internal conversion electrons directly with that of electrons accelerated through an accurately known potential difference. The result constitutes a complementary and independent check of other methods.

I. METHOD

The momentum of electrons focused by an iron-free magnetic spectrometer is proportional to the current through the coils of the spectrometer. Hence, electrons of unknown momentum can be compared with those of known momentum by a simple measurement of the ratio of two currents. Electrons of known momentum were obtained by acceleration in an electron gun through a known potential difference. In principle the method is very simple; however, considerable care is required in order to achieve substantial precision.

A. Spectrometer

A uniform magnetic field solenoidal spectrometer[13] employing a ring focus was used. The delimiting baffles of the spectrometer were set to transmit ~1 percent of isotropically emitted electrons. The theoretical inverse momentum resolution (full width at half-maximum) for the optimum source diameter (0.014 in.) at this setting is 0.10 percent.

Both the vertical and horizontal components of the earth's magnetic field were neutralized. The residual field was less than 0.01 gauss, and constant to about one-fifth of this value. The lowest spectrometer field required for the experiment was ~40 gauss. The effect on the spectrometer calibration of masses of iron deliberately placed nearby was studied. It was concluded that no undetected iron in the vicinity of the instrument could influence the results. In addition, the momentum of accelerated electrons *vs* spectrometer current was studied from 1.9- to 18.6-kv accelerating potential with no indication of nonlinearity.

B. Electron Gun

A diagram of the electron gun is shown in Fig. 1. A set of small insulated electrodes was placed on the

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[11] We are indebted to Dr. DuMond for informing us of these results prior to publication (see reference 9).

[12] Page, Stehle, and Gunst, Phys. Rev. 89, 1273 (1953).

[13] F. H. Schmidt, Rev. Sci. Instr. 23, 361 (1952).

baffle structure of the spectrometer. These were used to insure that the current issuing from the "gun" was constant from 34° to 36° elevation angles. The positions of the wolfram filament and of the inner electrode, both of which affected the direction of the electron beam, could be adjusted during operation. The entire internal "gun" structure could be rotated in order to pass electrons through the spectrometer at any desired azimuthal angle. The assembly entered the spectrometer vacuum through an air lock. Its position within the spectrometer was reproducible to within 0.001 inch.

C. Thorium B Sources

Thorium B was deposited on thin ($\sim$50 μg/cm^2) Nylon films over a circular area 0.014 inch in diameter. A jig fixture positioned accurately the film and supporting ring. The Nylon was gently clamped to a Lucite disk which covered the radiothorium container. A 0.014-inch hole in the Lucite allowed the active material to be attracted to the Nylon film by a 600-volts negative potential. With the limited supply of radiothorium available ($\sim$2 mg Ra equivalent) sources prepared in this manner were adequately strong for observation of the *F* line in the spectrometer, but the other well-known lines were too weak. Accordingly, comparisons of the other lines with the *F* line were made with larger (0.056-inch) diameter sources. The spectrometer was set at $\sim$2 percent transmission for these measurements.

After each measurement with the electron gun, the disk *K* (see Fig. 1) was removed and a thorium B source holder substituted in its place. The position of the active deposit was shown to coincide with the original position of the hole in disk *K* by means of a collimating hole and G-M counter mounted in a jig fixture.

D. Electrical Apparatus and Measurements

A 1- to 20-kv power supply similar to one described by Pepinsky and Jarmotz[14,15] was used to accelerate electrons in the gun. Under operating conditions the maximum voltage variations due to ripple and drift of the balance battery did not exceed one part in 30 000.

Two potential dividers were used to measure the high voltage. One of these, the "standard," was composed of 48–20 000-ohm manganin wire units, and 3–148.15-ohm manganin wire units. The former could be placed in series, and the latter in parallel; the ratio between them is then 18 500. Alternatively, the large units could be placed in parallel, and the small units in series; the ratio between them is then one. Accordingly, a direct comparison can be made between a standard cell and $\sim$18.5 kv. The theory of the method and construction details of a similar resistor have recently been published by Harris.[16] A second potential divider consisting of a 60-megohm nichrome oil-immersed temperature-controlled resistor was compared with the "standard" divider prior to each run. Three unsaturated Weston standard cells constituted the primary voltage standard. These were calibrated by the Bureau of Standards shortly before and immediately after the experiment. Most of the potential drop across the low-voltage section of the high-voltage dividers was balanced out by a standard cell placed in series with a Leeds and Northrup type-K potentiometer. Therefore, only a small residual potential was measured by the potentiometer.

Accelerating voltages were measured to ±0.005 percent. These were corrected for the work function (4.5 v) of the wolfram filament in the electron gun. All other important metals in the system were similar, so that no corrections for contact potentials were required.

For the comparison of the *F* line with accelerated electrons the current for the spectrometer coils was supplied from a set of large storage batteries. It was constant to ±0.002 percent during a run. Relative values of the coil currents were determined by measuring the potential drop across a precision 100-ampere Leeds and Northrup 0.01-ohm manganin shunt. The currents required for 18.5-kev electrons and the *F* line were $\sim$4.2 and 12.8 amperes, respectively. A divider consisting of three equal resistances was placed across the 0.01-ohm shunt. The potential appearing across all three was measured on a type-K potentiometer when operating at the lower current value. For the higher current, the potential across each section of the divider was measured. Therefore, very nearly the same place

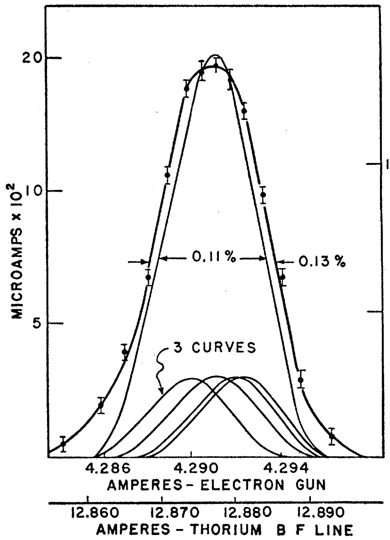

FIG. 2. Thorium B *F* line shown superimposed on the "line" obtained from the electron gun. The electron line was measured for six azimuthal angles around the ring focus and summed to give the resultant curve. The difference in width between the *F* line and the electron line is attributed to a natural width of the *K*-shell energy level in bismuth.

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[14] R. Pepinsky and P. Jarmotz, Rev. Sci. Instr. **19**, 247 (1948).

[15] G. Schwartz and E. Byerly, Rev. Sci. Instr. **19**, 279 (1948).

[16] J. N. Harris, Rev. Sci. Instr. **23**, 409 (1952).

TABLE I. Momenta and energies of useful calibration lines in the decay of thorium B.

Th line	Investigator	Electron momentum in gauss-cm	Gamma-ray energy in kev
F	Siegbahn[a]	1384	
F	Craig[b]	1388.5 ±0.3	
F	Lindström[c]	1388.55±0.15[d]	238.63 ±0.04[d]
F	Muller *et al.*[e]		238.595±0.032[f]
F	Present work	1388.56±0.21	238.63 ±0.06
A	Craig[b]	533.66±0.12	
A	Present work[g]	534.11±0.22	
I	Craig[b]	1753.9 ±0.4	
I	Lindström[c]	1754.01±0.20[d]	238.62 ±0.04[d]
I	Present work[g]	1754.0 ±0.7	
L	Lindström[c]	2607.17±0.30[d]	510.85 ±0.08[d]
L	Muller *et al.*[e]		510.90 ±0.09[f]
L	Present work[g]	2606.9 ±1.0	
X	Lindström[h]	9986.7 ±1.5	2614.25 ±0.50
X	Brown[h]	9988 ±2.0	2614.7 ±0.6
X	Present work	9985 ±5.0	

[a] See reference 1.
[b] See reference 8.
[c] See reference 7.
[d] The error listed here is that quoted in the full report in Arkiv Fysik, reference 7.
[e] See reference 9.
[f] Crystal spectrometer measurements.
[g] By comparison with the *F* line at 0.4 percent resolution.
[h] See reference 10.

on the potentiometer slide wire could be used for each of the precision comparison measurements.

II. RESULTS AND DISCUSSION

Data for a typical run on the *F* line and the electron gun are shown in Fig. 2. The focused electron currents from the gun at constant accelerating potential are plotted *vs* spectrometer current for 6 equally spaced azimuthal angles. The variation as a function of angle is due to slight inhomogeneities in the spectrometer magnetic field and to minor mechanical variations.[17] The six curves are added together to obtain the resultant electron-gun transmission curve. The *F* line is shown superimposed on the electron-gun data. The full line width at half-maximum for the accelerated electrons is 0.11 percent, whereas the width for the *F* line is 0.13 percent. The most probable cause for this difference in width is a natural spread of ~0.02 percent, or ~50 ev, in energy of the *F* line. A similar effect was observed by Slätis and Lindström,[18] and attributed by them to the distribution in energy of the *K*-shell electrons.

The average value of six measurements of the momentum of the *F* line are given in Table I, together with other recent work. The agreement among the various investigations, each by a different method, is very good. In converting the energy of the accelerated electrons into momentum, and in calculating the energy of the *F*-line electrons, the least-squares values of the atomic constants given by DuMond and Cohen[19] were used. The *K*-electron binding energy for bismuth was taken from the tables of Cauchois and Hulubei.[20] The internal consistency of the six independent determinations is ±0.01 percent; the probable error quoted in Table I includes the various other uncertainties.

The data for the other thorium lines listed in Table I were obtained with the spectrometer set for ~2 percent transmission corresponding to ~0.4 percent resolution. The focusing current at the peak of each line was compared with that for the *F* line. For these measurements a motor-generator set was used to supply the current, and a type-K potentiometer was employed in the normal manner to determine the coil current. With the possible exception of the *A* line, the agreement between our values and those of others is excellent.

We wish to thank G. L. Keister for the loan of a vacuum evaporator, Lee Meyer for assistance with tedious measurements, and Max Henker for skill in making the numerous small mechanical parts of the electron-gun and standard resistors.

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[17] The width of the ring slit is only 0.007 inch.

[18] H. Slätis and G. Lindström, Phys. Rev. **88**, 1429 (1952).

[19] J. W. M. DuMond and E. R. Cohen, Phys. Rev. **82**, 555 (1951).

[20] J. Cauchois and H. Hulubei, *Longueurs d'Onde des Emissions X* (Hermann et Cie, Paris, 1947).