Beta Spectrum of Bi^{212} (ThC)

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The beta spectrum of Bi^{212} was measured by using a short magnetic-lens beta spectrometer. Pb^{212} in equilibrium with its decay products was used as a source. The spectrum of Bi^{212} was separated from the other component spectra by measuring the coincidences between the beta spectrum and the alpha particles from Po^{212} (the nucleus formed after the beta decay of Bi^{212}) emitted with the half-life of 3×10^{-7} sec.

One obtains a complex spectrum whose maximum energy is 2.27 Mev. The beta components were separated by Fermi plots. The end points for the component spectra and their relative intensities were found. Spins and parity assignments for the excited levels of Po^{212} were made.

1. INTRODUCTION

THE radiations emitted from a source of Pb^{212} (ThB) in equilibrium with its products has been studied by many authors. Although in particular, the β-decay of Bi^{212} (ThC) has been investigated, our knowledge of this decay has been very inadequate, largely because of technical difficulties in separating the spectrum of Bi^{212} in the presence of other complex spectra. In this work the β spectrum of Bi^{212} has been separated by measuring coincidences between β particles and the 8.78-Mev α particles of Po^{212} (which are delayed by 3×10^{-7} sec with respect to the β particles of Bi^{212}).

Figure 1 shows the disintegration scheme of Pb^{212} in equilibrium with its decay products. In one third of the cases Bi^{212} decays to Tl^{208} which then disintegrates by beta decay to stable Pb^{208} with a half-life of 3 minutes. In two thirds of the cases Bi^{212} disintegrates by beta decay to Po^{212} which subsequently decays by alpha emission to Pb^{208} with a half-life of 3×10^{-7} sec. The energy distributions of the beta spectra of Bi^{212} and Tl^{208} are roughly in the same range and, moreover, their spectra are complex, containing many components with different end points. A direct measurement of the spectrum will therefore lead to a complicated superposition of the two spectra. In addition, in the lower range of energy (less than 0.569 Mev) the beta spectrum of Pb^{212} may contribute, if a chemical completely successful separation of lead from bismuth is not carried out.

Martin, Richardson, and Hsü[1] separated the beta spectrum of Tl^{208} by collecting the recoil nuclei of this isotope which had been obtained after alpha decay of Bi^{212}. Pb^{212} in equilibrium with its decay products was used as the initial source and the recoil nuclei of Tl^{208} were collected on a special support which served as a source for the spectrometer. There is a serious drawback in this method however, because of the relatively short half-life of Tl^{208} (3 minutes), and the measurement had to be made using sources of recoil nuclei, the results being normalized. In later work, Martin and Richardson[2] measured the beta spectra of Bi^{212} and Tl^{208} which were in equilibrium with Bi^{212}. The spectrum of Pb^{212} was eliminated by a chemical separation between bismuth and lead. The beta spectrum of Bi^{212} was obtained by subtraction of the beta spectrum of Tl^{208} which was obtained in the previous work, from the compound spectrum in the later work. In their work on the β spectrum of Tl^{208} the authors were disturbed by aggregate recoil which resulted in Pb^{212} nuclei's being carried away, and the measured spectrum had to be corrected for this activity. Furthermore, the authors had to take into account the incomplete chemical separation of Pb^{212}. Because of all the reasons mentioned above, and the indirectness of the method, there was an obvious uncertainty about the resulting shape of the beta spectrum of Bi^{212}.

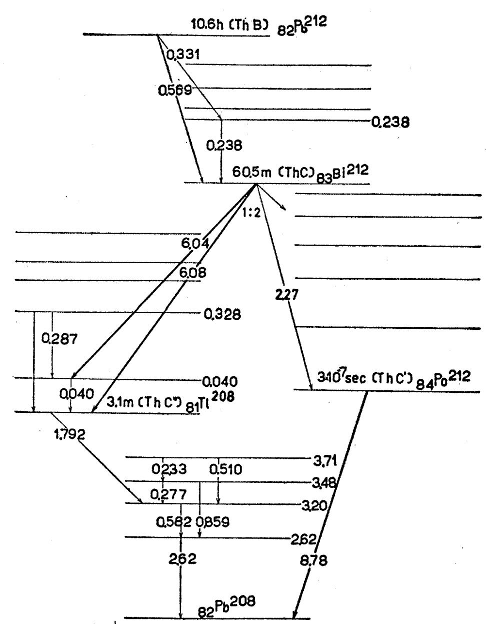

FIG. 1. The disintegration scheme of Pb^{212} in equilibrium with its decay products.

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[1] Martin, Richardson, and Hsü, Proc. Phys. Soc. (London) **A60**, 466 (1948).

[2] D. G. E. Martin and H. O. W. Richardson, Proc. Roy. Soc. (London) **A195**, 287 (1949).

These various difficulties were overcome in the present work, by utilizing the fact that Po^{212} (which is produced after the beta decay of Bi^{212}) decays by the emission of α particles of 8.78 Mev with a half-life of 3×10^{-7} sec. Coincidence measurements between the β particles from a source of Pb^{212} in equilibrium with its decay products and 8.78-Mev alpha particles should thus effectively separate the beta spectrum of Bi^{212} from the compound spectrum including those of the other isotopes.

The components of the complex spectrum found in this way were separated by Fermi plots. The end points for the component spectra and their relative intensity were found. These results are compared with previous work on the γ-ray spectrum produced in the de-excitation of excited levels of Po^{212}. Spins and parity assignments for the excited levels of Po^{212} are made.

2. EXPERIMENTAL ARRANGEMENT

The experimental arrangement was similar to the general arrangement described in a previous work by Burde and Cohen[3] on the spectrum of L Auger electrons from Tl^{208} and Bi^{212}. The beta spectrum was measured by using a short-lens beta spectrometer. A Geiger counter was used to detect the electrons. For energies above 200 kev a 1-mg/cm^2 mica window was used. Below 200 kev the window was prepared from alternating layers of Zapon and Formvar supported on thin wires of tungsten. The absorption through this window was negligible for electrons down to 17 kev.

The alpha scintillator was, as in the previous work,[3] a thin wafer of plastic scintillator situated behind the source, 8 mm in diameter and 0.2 mm thick, which sat in a suitable depression at the top end of the light pipe. A source of Pb^{212} in equilibrium with its decay products was obtained by collecting recoil nuclei from radiothorium emanation on a circle 1.5 mm in diameter on a foil of aluminum of thickness 0.17 mg/cm^2. The latter was centered on a 10-mm diameter thin Zapon film, supported on a light aluminum frame 1 mm high. This was inserted into the depression of the light pipe above the plastic scintillator. The source was grounded and covered with a film of Zapon of thickness 10 μg/cm^2 to stop the recoil nuclei of Tl^{208} and the associated aggregate recoil.

In order to obtain the coincidence spectrum with a satisfactory statistical accuracy, it was important to use a large solid angle for the alpha-particle detector which had to sustain a high counting rate without losses. In investigating this isotope it had to be taken into account that there was a limitation in the duration of the time for every measured point of the spectrum. This was due to the effective lifetime of each source used (the half-life of Pb^{212} is 10.6 hours). There existed a lower limit to the resolving time of the coincidence system which could be used due to the half-life of Po^{212} of 3×10^{-7} sec, this limiting the source strength used.

The distance between the source and scintillator was 1 mm and the solid angle subtended at the source was about $4\pi/3$. It was not desirable to move the source nearer to the scintillator, because many electrons would then enter the scintillator obliquely and would have a large path length in the scintillator. In consequence these electrons might give pulses comparable in height to those produced by alpha particles. As was shown in a previous work,[3] under the above conditions, the pulses of the two groups of alpha particles were clearly displayed above the electron pulses, the higher group being due to alpha particles of energy 8.78 Mev. This was the group under consideration, and could be easily separated by discrimination.

The resolving time of the coincidence unit was 3.6×10^{-7} sec and during the period of the measurements this time was often checked. This was essential since a drift in the resolving time would result in an alteration of the number of true coincidences, the lifetime of Po^{212} being comparable to the coincidence resolving time. For a counting rate of α particles which did not exceed 40 000 counts per second, no counting losses occurred in the scintillation system including the scalers, and no losses were obtained in the coincidence unit. It was important to avoid losses in order to prevent a distortion in the observed shape of the beta spectrum due to the change of the source activity with time. The change in the activity of the source was taken into account by dividing the number of the true coincidences by the number of the counts recorded by the scintillator. The resolving time was found by measuring the number of random coincidences of two independent sources. The random coincidences for every point were calculated and subtracted from the total number of the total coincidences.

As it was necessary to measure electrons of energy exceeding 2 Mev, the effect of the magnetic field of the spectrometer coil on the photomultiplier was investigated. A disturbing effect was noticed even for magnetic fields necessary to focus electrons of 1.3 Mev. To cancel this disturbance the photomultiplier was covered with a thick iron housing. The presence of this iron at the end of the light pipe produced no noticeable effect on the performance of the spectrometer even in the lowest range of energy under investigation. This was checked by comparing the shape of the 24.5-kev "A" line, with and without the iron housing.

The measurements were carried out at a momentum resolution of 4% in the β spectrometer. Coincidences were recorded during 30 minutes for each value of momentum chosen. The measurements of ten to fifteen points took a day's run. During nine days about a hundred different points were measured, every day a new source having been inserted. After every insertion, special attention was paid that the experimental conditions be preserved, and, in addition, during every day's

[3] J. Burde and S. G. Cohen, Phys. Rev. **104**, 1085 (1956).

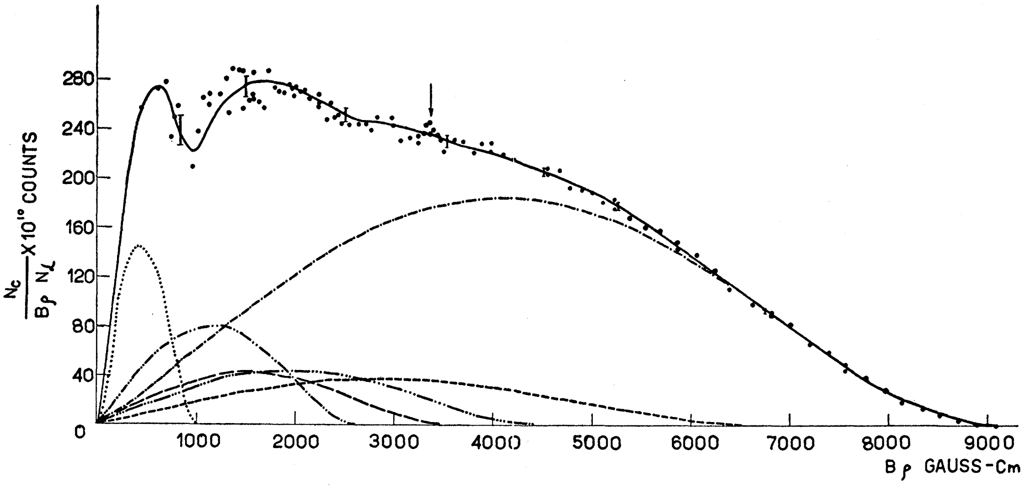

FIG. 2. The upper curve shows the experimental results. The ordinate gives the number of true coincidences N_c divided by the momentum $B\rho$ and by the number of alpha particles N_α detected by the scintillator. The arrow points at the position of the converted line in the K shell of the 0.72-Mev transition. The vertical lines on the curve indicate the statistical errors. The resolved beta components are given by six broken curves.

series of measurements, a recurring point was measured. Moreover a set of measurements were made which included points of all the sets to check the normalization.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The upper curve of Fig. 2 shows the experimental results. The ordinate gives the number of true coincidences divided by the momentum and by the number of alpha particles detected by the scintillator. The arrow points at the position of the coverted line in the K shell of the 0.72-Mev transition. The vertical lines on the curve indicate the statistical errors. More than five thousand true coincidence for each chosen value of the momentum were recorded for the middle part of the spectrum (between 400 kev and 1500 kev), and in this region the number of random coincidences was between 15% and 25% of the true coincidences. In the region of 50 kev a thousand true coincidences were recorded for each point and the random coincidences were 80% of the true. For the high-energy part of the spectrum fair statistical accuracy was obtained, since the momentum resolution of the lens spectrometer is independent of momentum and the spectrometer therefore transmits a wider range of momenta at the higher momentum settings.

A Fermi plot of the most energetic part of the spectrum did not differ from a straight line within statistical accuracy. The end point of the spectrum corresponding to the beta transition between the ground state of Bi^{212} and the ground state of Po^{212} was found to be 2.27 Mev, in good agreement with the work of Martin and Richardson.[2] In the Fermi plot there was a clear change in slope at an energy of 1.55 Mev, indicating an additional less energetic component corresponding to a transition to an excited level of Po^{212} at an energy 0.72 Mev. The existence of the level is known from the 0.72-Mev gamma rays accompanying the decay of Bi^{212}, and from the existence of long-range alpha particles whose energy exceed those that decay from the ground state of Po^{212} by 0.73 Mev.[4]

Po^{212} is an even-even nucleus whose ground state is undoubtedly 0+. Furthermore, from the measurement of the internal conversion for the 0.72-Mev, transition, Martin and Richardson[2] deduced that this transition is electric quadrupole, leading to 2+ assignment for the first excited level, as is to be generally expected for even-even nuclei. The shape of the most energetic component indicates that the degree of forbiddenness cannot exceed the first. This removes the possibility of a transition with a spin change of two (unique transition) which would have led to a shape that differed significantly from an allowed shape. This leaves two alternatives for spin of the ground state of Bi^{212}, either 0 or 1. From the $\log(ft)$ value for the most energetic component of the spectrum (7.6) the ground-to-ground transition has to be classified as first-forbidden, indicating odd parity for the ground state of Bi^{212}.

The possibility of a 0− assignment for the ground state of Bi^{212} was investigated. In this case the transition is of the type $0- \rightarrow 0+$. The experimental points in the Fermi plot for the most energetic component were corrected for the suitable interaction. Under the present assumption there must be a spin change of two for the transition to the 0.72-Mev level. The experimental points after subtracting the first component were corrected for the tensor interaction characteristic of a unique transition. The curve thus obtained differed significantly from a straight line, thereby contradicting the original assumption.

The remaining alternative is that the ground state of Bi^{212} is 1−. This result is in agreement with the work of Horton[5] who arrived at this result from measurements

[4] A. Rytz, Compt. rend. **233**, 790 (1951).
[5] J. W. Horton, Phys. Rev. **101**, 717 (1956).

of the angular correlation between alpha particles emitted from Bi^{212} and gamma rays from the 40-kev excited level of Tl^{208}. The final resolution of the spectrum into its component spectra was carried out according to this assignment. The ground-to-ground transition is then of the type $1- \rightarrow 0+$. As the element under investigation has a high Z, the energy-dependent terms in the matrix element for this transition is overwhelmed by the energy-independent Coulomb term which is proportional to $Ze^2/2R$ (R being the nuclear radius), and so the expected deviations from an allowed shape should be small. Nevertheless, it is desirable to correct for the deviation from the allowed shape in order to extrapolate to lower energies correctly, and to obtain by subtraction the lower-energy components.

The Fermi plot was therefore corrected for the first-forbidden ground-to-ground transition by dividing the ordinates of the points by the square root of the appropriate energy-dependent coefficient known as the shape factor for the following three different assumptions concerning the interactions: (1) scalar interaction, (2) tensor interaction, and (3) equal mixtures of scalar and tensor interactions. In the mixed interaction the interference term, assumed to be small in comparison to the other terms, was neglected.

The shape of the second component, found by subtraction of the extrapolated most energetic component, was sensitive to the type of correction applied to the first component. A good straight line was obtained for Fermi plot of the second component when the first was corrected for the equally mixed scalar and tensor interaction, whereas for the other possibilities, including the possibility for the uncorrected allowed shape, a fit of the points to a straight line was definitely less successful. Figure 3 shows the experimental points in a Fermi plot which was corrected for an equal mixture of scalar and tensor interaction, neglecting the interference term. The straight line gives the most energetic component which intersects the abscissa at an energy of 2.27 Mev. At about the energy of 1.5 Mev, the experimental points begin to deviate from the straight line as a consequence of the second superimposed component. The deviation of the Fermi plot from a straight line for the second component (which is also first-forbidden), the energy of which is lower, should be less than for the first component. The subtracted experimental points of the second component were not corrected for the first-forbidden interactions, both for this reason and since the accuracy of the shape of a spectrum determined by subtraction is reduced. The straight line fitted to the subtracted spectrum in the Fermi plot intersects the abscissa at the energy of 1.55 Mev, and near the energy of 0.9 Mev there is a deviation of the experimental points from the straight line. By subtracting the second component, a straight line was obtained in a Fermi plot, the intersection of which is at the energy of 0.93 Mev. This indicated that a third β spectrum excites a second level in Po^{212} at 1.34 Mev.

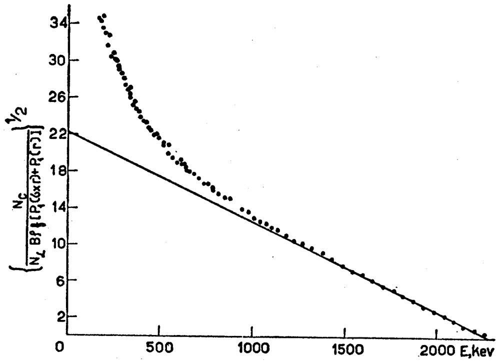

FIG. 3. The experimental points in a Fermi plot which was corrected for an equal mixture of scalar and tensor interaction neglecting the interference term, for **a** first-forbidden transition with a change of spin one. The straight line gives the most energetic component which intersects the abscissa at an energy of 2.27 Mev. N_c gives the number of true coincidences, N_α the number of alpha particles, and f the function of Fermi. $P_1(\boldsymbol{\sigma}\times\mathbf{r})$ and $P_1(\mathbf{r})$ indicate the tensor and scalar interactions, respectively.

TABLE I. Summary of experimental data on the complex beta spectra in the decay of Bi^{212}.

End point (Mev)	log(ft) value	Intensity of beta transition (percent): Assuming allowed shape for most energetic spectrum	Correcting for first forbidden shape in most energetic spectrum	Energy of level excited by the beta transition (Mev)	Spin and parity assignment
2.27	7.6	66	63	0	0+
1.55	7.9	8.5	10	0.72	2+
0.93	7.1	5.5	7.5	1.34	1+ or 2+
0.67	6.7	6	6	1.6	2+
0.45	6.1	9	8.5	1.8	2+
0.08	4	5	5	2.19	1−

A 1.34-Mev gamma ray has been observed by Johansson[6] and also by Latyshev.[7] But these authors interpreted the gamma ray as being emitted in a transition from the 2.2-Mev level to a 0.84-Mev level which they assumed to exist. Johansson claims that the intensity of the gamma ray from this level was equal to that of the 0.72-Mev gamma ray. In coincidence measurements which had been made at our laboratory[8] between the 8.78-Mev alpha particles and the gamma rays, a gamma ray of energy 1.34 Mev was found, but no 0.84-Mev gamma ray could be detected in coincidence with these alpha particles. The intensity of such a gamma ray if present must be less than ten percent of the 0.72-Mev gamma ray. These experimental results thus confirm the assumption of a level at 1.34 Mev.

In the lower energy region three further component spectra were observed. Obviously, one could not expect to get the exact shape for these components, but as-

[6] A. Johansson, Arkiv Mat., Astron. Fysik **34A**, No. 9 (1947).
[7] G. D. Latyshev, Revs. Modern Phys. **19**, 132 (1947).
[8] Wiener, Burde, and Ofer (to be published).

suming that their Fermi plots do not differ much from straight lines, one could get the end points within definite limit of accuracy and the relative intensity for the components. The last assumption seems quite reasonable since the *ft* values for the low-energy components are lower than for the two high-energy components so that the degree of forbiddenness cannot exceed the first.

By subtracting the third component, a straight line in a Fermi plot intersects at the energy of 0.67 ± 0.05 Mev, which corresponds to a transition of the fourth beta component to an excited level at the energy between 1.55 Mev and 1.65 Mev. The fourth component transition is thus consistent with an excitation of the 1.6-Mev level of Po^{212}.

In a similar way the end point of the fifth component was found at an energy of 0.45 ± 0.04 Mev which is consistent with a transition to the 1.8-Mev excited level. The existence of the 1.6-Mev and 1.8-Mev levels is known from previous work on the gamma-ray spectra and the energy of the long-range alpha particles. The end point of the less energetic component was found, with relatively greater accuracy, at an energy of 0.085 ± 0.005 Mev, which corresponds to the excitation of the 2.19-Mev level of Po^{212}. The existence of this level is also known from previous work on the gamma-ray spectra.

The resolved beta spectra are plotted in Fig. 2. Their ordinates are added in the upper curve, which, as can be seen, fit quite well the experimental points plotted in the same figure. From the relative intensities of the spectra the $\log(ft)$ values were calculated. The experimental data on the β spectra is summarized in Table I. The relative intensities obtained when the most energetic spectrum is left uncorrected for a first-forbidden transition is also given for comparison. It is seen that differences in intensities of about a few percent are involved for some of the transitions. The end points are not sensitive to whether a correction is made or not. Figure 4 shows the decay scheme for the β decay of Bi^{212}, based on the present work. The presence of a gamma ray of energy 1.5 Mev[7] can be explained by a transition between the levels 2.19 Mev and 0.72 Mev; the known 1.1-Mev[6] gamma ray can occur as transition between the levels 1.8 and 0.72 Mev.

From the $\log(ft)$ value for the least energetic component spectrum (end point 0.08 Mev) it is clear that the beta transition to the 2.19-Mev level is allowed, so that the parity of this level must be odd. As there is a gamma transition to the ground state from this level, the possibility of an $0-$ assignment is excluded and we are left with either $1-$ or $2-$. According to Latyshev,[7] the gamma transitions from the 2.19-Mev level to the 0.72-Mev level and to the ground state are both dipole. Thus the 2.19-Mev level should be $1-$.

Since there are gamma transitions to the ground state from all the three remaining higher levels, their spins should be different from zero. Furthermore as the

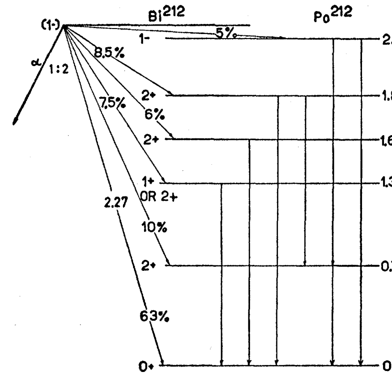

FIG. 4. The beta-decay scheme of Bi^{212}, based on the present work. The gamma rays were measured by Johansson,[6] Latyshev,[7] and Wiener *et al.*[8]

$\log(ft)$ values for the corresponding beta transitions point to first forbidden transitions, the parities of the levels should be even. The spins of these levels could not be 3, because the shape of the beta components are not of the unique transition type. There remain thus two alternatives for the spins of these levels: 1 or 2. According to Latyshev,[7] the 1.6-Mev and 1.8-Mev transitions are of quadrupole transitions, and therefore the assignment of these two levels should be $2+$.

According to Latyshev,[7] the 1.34-Mev transition is dipole and thus the resulting assignment for this level should be $1+$. This assignment, however, is in disagreement with the empirical observation of Glaubman[9] (which has been explained theoretically by Talmi[10] on the basis of the shell model) that low-lying levels of even spin in even-even nuclei should have even parity, and the levels of odd spins should have odd parity. Although the 1.34-Mev level can hardly be classified as a low-lying level and it is doubtful whether Glaubman's observation should apply in this case, the remaining level assignment is in agreement with this observation. Latyshev determined the multipolarity of the 1.34-Mev gamma transition by measuring the conversion coefficient for internal pair production; however, his value for the intensity of the 1.34-Mev gamma ray is 1.8% which differs from Johansson's value of 4.5% for the same gamma-ray transition. The latter figure might indicate a quadrupole transition on the basis of Latyshev's calculations. Johansson's result is in reasonable agreement with the measurement of the intensity of the beta transition to the 1.34-Mev level (5.5%–7.5%) in the present work, in particular if one does not exclude the possibility of a weak gamma-ray transition to the 0.72-Mev level, which might be unobserved in the presence of the much stronger 0.72-Mev gamma ray. Therefore the two alternatives are left for the spin assignment of the 1.34-Mev level.

The 6% beta excitation of the 1.6-Mev level is in

[9] M. J. Glaubman, Phys. Rev. **90**, 1000 (1953).
[10] I. Talmi, Phys. Rev. **90**, 1001 (1953).

good agreement with Latyshev's value of 5% and Johansson's value of 7% for the intensity of the 1.6-Mev gamma ray. The 5% intensity of the beta transition to the 2.2-Mev level is consistent with the combined intensities of the 2.2-Mev and the 1.5-Mev gamma rays (4.3% according to Latyshev). The 8.5%–9% beta excitation of the 1.8-Mev level is consistent with the sum of Latyshev's value for the 1.8-Mev gamma-ray intensity and Johansson's figure for the 1.03-Mev gamma (together 8.6%). Finally, Johansson's value of 18.5% for the 0.72-Mev gamma is in fair agreement with the combined intensities of Johansson's result for the 1.03 Mev gamma and Latyshev's value for the 1.5-Mev gamma and the beta excitation of the 0.72-Mev level (together 15.8%–17.3%).

As was indicated above, the 0.84-Mev gamma ray reported by Johansson was not found in alpha-gamma coincidence measurements[8] and is most probably the 0.859-Mev gamma transition in Pb^{208}.

ACKNOWLEDGMENT

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Gyromagnetic Ratio of the 10^{-8}-sec State of Ta^{181}†

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The gyromagnetic ratio of the 482-kev state of Ta^{181}(10^{-8}-sec) has been measured by angular correlation techniques and found to be $+1.23\pm0.05$ nuclear units.

THE present measurement of the gyromagnetic ratio of the 482-kev 10^{-8}-sec state[1] of Ta^{181} (Fig. 1) was undertaken to improve the accuracy of our previous result[2] and to obtain additional information about the effect of extranuclear fields on the results. Since our preliminary report, a group in Zurich[3] has made a similar measurement.

Hafnium metal, irradiated in the Reactor CP-5 at the Argonne National Laboratory, was dissolved in concentrated hydrofluoric acid. The sources were contained in Teflon holders with the active volume in a cylinder 3.2 mm in diameter and about 3.2 mm high.

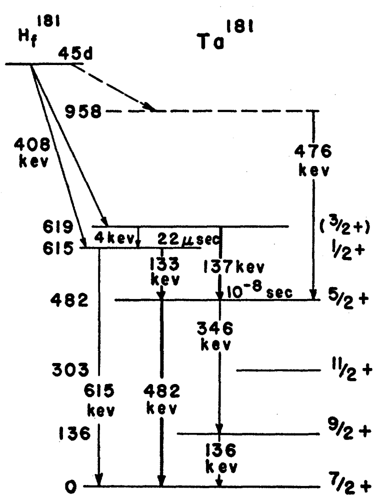

FIG. 1. Decay scheme of Hf^{181} as given by Boehm and Marmier.[1] The dark lines indicate the gamma rays involved in the present measurements.

The 482-kev and 133-kev or 137-kev gamma rays were detected by cylindrical NaI(Tl) crystals 3.8 cm in diameter and 2.54 cm long. These crystals were fastened to 28-cm Lucite light pipes which were optically bonded to fourteen-stage photomultipliers (6810). A fast-slow coincidence circuit was used for the measurements. The fast coincidence circuit was similar to the circuit described by Bell, Graham, and Petch,[4] and resolving times (2τ) from 20 to 70 mμsec were used during the course of the measurements. The pulses for the fast coincidence circuit were limited by EFP-60, secondary-emission pentodes, and fed to the fast-coincidence circuit without amplification. Pulses from the tenth dynodes of the 6810 multipliers were utilized for pulse height analysis. The system required a coincidence of the output pulses of each of the two single-channel analyzers, and the fast-coincidence circuit in order to register an event.

For a liquid source, with a magnetic field H applied perpendicularly to the plane of the detectors of the two gamma rays, the directional correlation is given by[5]

$$W(\theta,\omega)=\int_0^\infty \sum_n A_n e^{-\lambda_n t}P_n(\cos[\theta+\omega t])e^{-t/\tau}F(t)dt, \quad (1)$$

where θ is the angle between the directions of emission of

† Work performed under the auspices of the U. S. Atomic Energy Commission.
[1] F. Boehm and P. Marmier, Phys. Rev. **103**, 342 (1956).
[2] S. Raboy and V. E. Krohn, Phys. Rev. **95**, 1689 (1954).
[3] Heer, Ruetschi, and Scherrer, Z. Naturforsch. **10a**, 834 (1955).
[4] Bell, Graham, and Petch, Can. J. Phys. **30**, 35 (1952).
[5] A. Abragam and R. V. Pound, Phys. Rev. **92**, 943 (1953).