It might be expected that the curves in Figs. 2 and 3 would show a dip after mass number 244 where the minor 152 neutron subshell observed in alpha decay energies would effect the level densities and the capture cross sections.[14] No such dip is seen.

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Evidence for 0^+ and 1^- Levels in U^{234} Populated in the One-Minute Beta Decay of Pa^{234}

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A directional correlation measurement has been performed on the 250-kev vs (751+795)-kev composite cascade in U^{234} following the 24-day beta decay of Th^{234} and the subsequent one-minute beta decay of Pa^{234}. The "770"-kev (751+795 kev) composite photopeak spectrum coincident with the 250-kev gamma ray was displayed on a multichannel pulse-height analyzer for different positions of the scintillation counters. From these spectra the directional correlations between the 250-kev gamma ray and the lower and upper sides of the 770-kev composite line were measured. The results together with other measurements are consistent with assignments of multipolarity $E1$ to the 250-, 751-, and 795-kev gamma rays and spin and parity assignments $0^+-1^--2^+$ and $0^+-1^--0^+$ to the levels involved in the 250–751 kev and 250–795 kev gamma-gamma cascades, respectively. Thus new levels are proposed at 795 and 1046 kev with spin and parity 1^- and 0^+, respectively.

INTRODUCTION

SINCE Th^{234} is obtained from natural uranium, it was one of the earliest radioactive nuclei to be studied. Nevertheless, there still exist uncertainties in the interpretation of this decay. One reason for this is that the electron conversion spectrum is masked by the presence of a very intense $Pa^{234} \rightarrow U^{234}$ ground-state beta-ray group (98% of all transitions) with end point 2300 kev. Another reason is that several transitions are strongly electron converted and, therefore, do not appear in the gamma-ray spectrum. For these reasons, it is especially important to complement beta- and gamma-ray spectroscopy of the Th^{234} decay by additional measurements. Consequently, we have attempted a gamma-gamma directional correlation measurement in order to lead to a clearer interpretation of the U^{234} level scheme.

Several outstanding features regarding the $Th^{234} \rightarrow Pa^{234} \rightarrow U^{234}$ decay are well known. The beta and gamma rays from the Th^{234} decay are relatively low in energy and do not interfere with the radiations from the Pa^{234} beta decay which are of higher energy. The Pa^{234} decay proceeds from two isomeric states with half-lives 1.18 minutes and 6.66 hours, respectively. The radiation from the one-minute decay is the more intense and dominates the spectrum. From scintillation counter measurements of the beta- and gamma-ray spectrum, and beta-gamma coincidence measurements, Johansson[1] has established the presence of a transition of energy 810 kev which must be completely converted in U^{234} and which is fed directly by beta decay from the one-minute isomer. Therefore, it is clear there must be a $0^+ \rightarrow 0^+$ ground state transition of this energy. DeHaan *et al.*[2] have measured the end-point energies of the beta-ray groups and their intensities in a beta-ray spectrometer. Ong Ping Hok *et al.*[3] have studied both the internal conversion electron spectrum with a beta-ray spectrometer and the gamma-ray spectrum with a scintillation counter. Complete references to earlier work are given by these authors.[1–3]

A decay scheme for the one-minute $Pa^{234} \rightarrow U^{234}$ decay has been proposed by Bjørnholm and Nielsen and is given in Fig. 1. The decay scheme is based principally on Bjørnholm and Nielsen's measurements[4] using the Copenhagen six-gap "orange" type beta-gamma coincidence spectrometer and the author's gamma-gamma coincidence measurements performed on a scintillation apparatus described in the next section.

The main pieces of evidence for proposing this decay scheme are as follows. The 811-kev transition is very strongly converted and, therefore, must have the multipolarity $E0$. Consequently, there must exist a level at 811 kev with spin and parity 0^+. The same 0^+ level has apparently been observed by Asaro and Perl-

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[1] S. A. E. Johansson, Phys. Rev. **96**, 1075 (1954).

[2] E. F. DeHaan, G. J. Sizoo, and P. Kramer, Physica **21**, 803 (1955).

[3] Ong Ping Hok, J. T. Verschoor, and P. Born, Physica **22**, 465 (1956).

[4] S. Bjørnholm and O. B. Nielsen (to be published). The author is indebted for the use of this information before its publication.

man[5] following Pu^{238} alpha decay to U^{234}. They assign an energy of 803 kev to this level. The first 2^+ rotational level at 44 kev in U^{234} is known to exist from Pu^{238} alpha decay.[5] Bjørnholm and Nielsen also find evidence for this level since they have detected L electrons from a 44-kev transition following Pa^{234} decay. They find these electrons coincident with gamma rays at 767 and 1000 kev. In addition to the ground-state beta group with end point 2300 kev, Bjørnholm and Nielsen find a beta group with end point of approximately 1500 kev in coincidence with a gamma ray at 767 kev and a beta group of end point 1250 kev in coincidence with gamma rays of approximately 250 kev and 1000 kev. Moreover, in the internal conversion spectrum they find K electrons from a 235-kev transition which are coincident with 767-kev gamma rays. Thus it appears reasonable that there is a level at 1046 kev which is populated directly by beta decay and which gives rise to both the 235-kev and 1000-kev transitions. Also, the 811-kev level must be populated partly by a 235-kev transition as well as directly by beta decay. However, in looking for gamma rays in coincidence with the 767-kev gamma ray, a photopeak was found by the author to be centered at 250±5 kev rather than at 235 kev as shown in Fig. 2. This is in agreement with Johansson[1] who was the first to report a 750–250 kev gamma-gamma cascade. Moreover, a 235-kev gamma ray could neither be observed in the singles spectrum nor in the spectrum coincident with the K electrons from the 811-kev transition.[4] Thus a lower limit is placed on the K internal conversion coefficient of the 235-kev transition which is high enough to exclude the possibility of $M1$, $E1$, and $E2$ for this transition. The value of the K/L ratio measured by Bjørnholm and

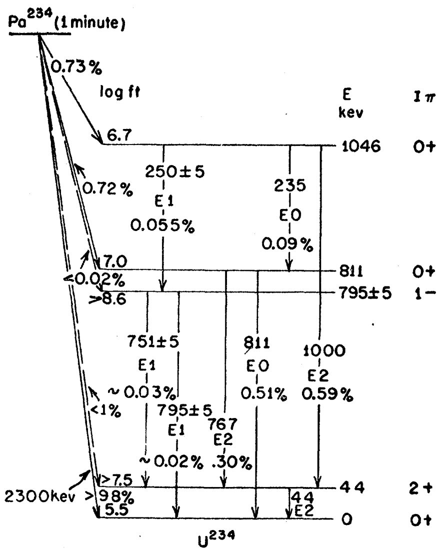

FIG. 1. The decay scheme of the one-minute isomer of Pa^{234} as proposed by Bjørnholm and Nielsen, reference 4.

[5] F. Asaro and I. Perlman, Phys. Rev. 94, 381 (1954).

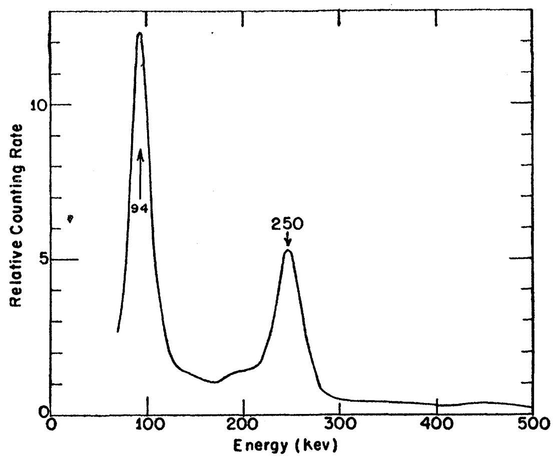

FIG. 2. The gamma-ray spectrum coincident with the 770-kev composite photopeak in Th^{234} decay.

Nielsen for the 235-kev transition establishes in addition that this transition is not $M2$. Thus $E0$ is strongly suggested for the 235-kev transition and the spin and parity 0^+ for the 1046-kev level. The scintillation spectrum of the gamma rays coincident with the 250-kev gamma ray are shown in Fig. 3. A peak is found at 770 kev but its width is too broad to be a single peak. The broadening can be explained if it is assumed that there are two gamma rays coincident with the 250-kev gamma ray with energies 44 kev apart, i.e., gamma rays with energies 751 and 795 kev which decay to the 44-kev and 0-kev levels, respectively. Should this be the case, it is then possible that the 250-kev gamma ray populates a new level at 795 kev while being emitted from the 1046-kev level already proposed. Bjørnholm and Nielsen were unable to detect the K electron from the 250-kev transition above the beta-ray background. However, they were able to place a limit on the K internal conversion coefficient of the 250-kev transition on the basis of which all possibilities except $E1$ can be ruled out for the multipolarity of this transition. Therefore, if the above assumptions are correct the 795-kev level must have spin and parity 1^-.

DIRECTIONAL CORRELATION MEASUREMENTS

A directional correlation measurement on the 250–"770" kev composite cascade was attempted in order to provide a crucial check on the spins of the levels proposed at 795 kev and 1046 kev. According to the decay scheme proposed in Fig. 1 the two cascades 250–751 kev and 250–795 kev should have very different directional correlations. Therefore, although the proposed gamma rays at 751 and 795 kev cannot be resolved from each other in the scintillation counter spectrum in coincidence with 250-kev gamma rays, the directional correlation of these coincidences should be a function of the pulse-height interval selected from the "770"-kev photopeak. For this reason the direc-

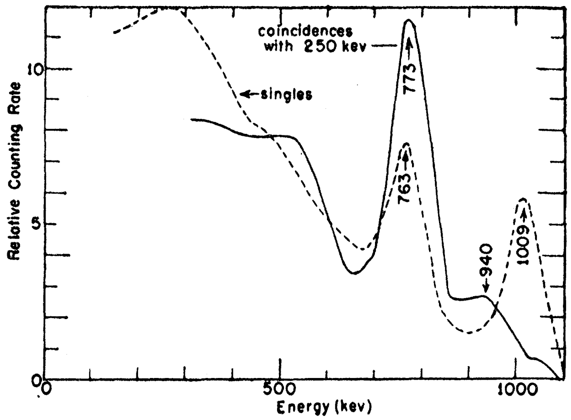

FIG. 3. Gamma-ray spectra of Th^{234} decay. (a) The high-energy portion of the singles spectrum. (b) The spectrum of gamma-rays coincident with the 250-kev region of the singles spectrum.

tional correlation was performed by displaying the 770-kev coincidence peak on a multichannel analyzer. Using this technique it was possible to analyze the upper and lower pulse-height regions of the peak separately.

Three scintillation counters were used in an arrangement shown in Fig. 4. The 250-kev photopeak was selected in Counter A and the 770-kev composite peak in Counters B and C. Coincidences were measured between Counters A and B and Counters A and C. In this way it was possible to make measurements at the 90° and 180° positions simultaneously. All three counters used $1\frac{1}{2}$-inch diameter by $1\frac{1}{2}$-inch long NaI (Tl) scintillation crystals mounted on RCA-6342 photomultiplier tubes. Conventional fast-slow coincidence circuits were used with the resolving time 2τ set at approximately 4×10^{-8} second.

The Th^{234} source was prepared by the conventional method[6] involving the extraction of Th^{234} into water from a solution of two kilograms of uranylnitrate in ether. The extracted Th^{234} was purified in a cation exchange column and the solution was placed in a 1.5-millimeter capillary tube for use.

In this experiment it is necessary to take special precaution against the occurrence of spurious coincidence due to scattering between the counters. The 1000-kev gamma ray may backscatter from the crystals of Counters B and C into the crystal of Counter A, thereby simulating a "770"-250 kev coincidence. In the case of the two counters at 90°, scattering between counters was practically eliminated by a 1-cm thick absorber placed between the counters. Lead absorbers 4 mm thick were also placed in front of Counters B and C in order to reduce backscattering between the two counters which were at 180°. A 3-mm aluminum absorber was also placed in front of Counter A in order to block the energetic 2.3-Mev beta rays.

[6] M. G. Bouissières, N. Marty, and M. I. Teillac, Compt. rend. **237**, 324 (1953).

The photopeak of the 250-kev gamma ray was selected in Counter A with a single-channel pulse-height selector. The coincident 770-kev composite line spectra from Counters B and C were displayed on a single multichannel analyzer. Spectrum B was displayed on the lower 50 channels of the multichannel analyzer and Spectrum C on the upper 50 channels. This was accomplished by using two independent gate circuits I and II which were gated, respectively, by the fast-slow coincidences A–B and A–C. In order to throw the spectrum of Counter C in the upper 50 channels, a flat pedestal was added to the gated signal pulses from Gate circuit II. Back bias was used on the multichannel analyzer so that the 50 channels available for displaying the spectra covered the 500- to 1000-kev region. Single-channel pulse-height selectors were used in addition on Counters B and C in order to cut out pulses which were outside this energy region. In this way, the spectrum displayed on the lower 50 channels was prevented from overlapping with the spectrum displayed on the upper 50 channels.

The coincidences A–B and A–C as recorded in the multichannel analyzer were measured for two configurations of Counters B and C. The first configuration was as shown in Fig. 4 where the angle between Counters A and B was 90° and between A and C, 180°. The second configuration was obtained by rotating Counters B and C together around the source so that the angle between Counters A and B was 180° and between A and C, 270°. The two configurations were run alternately, each run lasting one hour. On each multichannel coincidence spectrum of Counters B and C the eight adjacent channels which were centered on the composite 770-kev photopeak were selected. These channels covered approximately the width of this peak at half-maximum counting rate. After each one-hour run the counts collected in these eight channels were summed in three ways: (1) sum of all eight channels, (2) sum of lower four channels, and (3) sum of upper four channels. Just before and after changing the position of Counters B and C between each pair of one-hour runs, one-minute

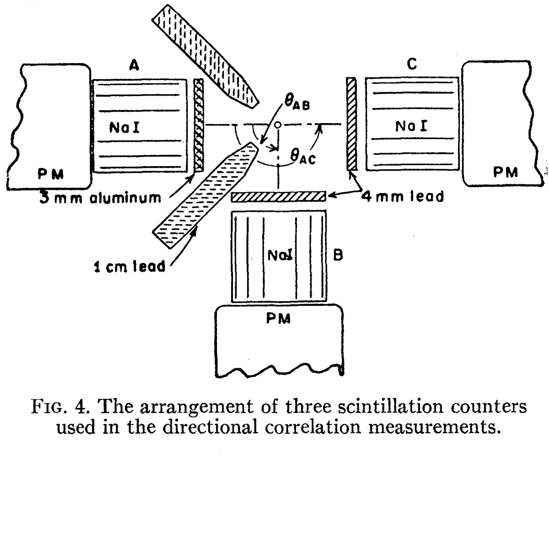

FIG. 4. The arrangement of three scintillation counters used in the directional correlation measurements.

runs were made to determine the singles rates from the single-channel pulse-height selectors following Counters B and C. These singles rates were used to normalize, respectively, the corresponding coincidence counts A–B and A–C (summed in the three ways discussed above) which were collected during the one-hour runs made before and after the angle change. Thus, changes in coincidence counting rate due to changes of the counter solid angle with the position of the counter were cancelled. After each one-hour run, the ratio of the normalized coincidence counts from the pair of counters at 180° to the pair at 90° was computed. The geometric mean of these ratios for each pair of one-hour runs gave the desired quantity, the 180° to 90° ratio of the directional correlation functions, $W(180°)/W(90°)$. In this way $W(180°)/W(90°)$ was determined for the lower and upper sides of the composite 770-kev photopeak as well as for the whole photopeak.

By using three counters instead of two to make directional correlation measurements, the rate of taking data is of course doubled. Moreover, results are obtained which are independent of source decay during the run, and which are less dependent on small drifts in the gains of the counters. For example, a small drift in Counter A will effect both the coincidence rates A–B and A–C in the same way so that the ratio of these rates is unaffected. Stability in Counters B and C is obtained if the counts are added for a fixed number of channels centered on the photopeak of interest in the coincidence spectrum. Thus, provided there are a sufficient number of channels covering the photopeak, the coincidence counts obtained should be relatively independent of small drifts in Counters B and C. In using this system, one does not normalize the coincidence counter with singles counts monitored concurrently during the coincidence run. Thus it is not necessary for the photopeaks of interest to stand out prominently in the singles spectra as it would be if normalization with singles counts were used to cancel counter drifts.

Of course, in experiments where the channels on the lower and upper sides of the photopeak are added separately, as is the case in the present measurements, the results will be more sensitive to gain drifts and it is important to use several cycles of runs of short duration to insure meaningful results. In all, seven pairs of runs were executed giving mutually consistent results within the limits expected by the statistical errors alone. Averaging the seven runs and making a slight correction for random coincidences, the lower four channels of the composite 770-kev coincidence photopeak give $W(180°)/W(90°)=1.19\pm0.03$ whereas the upper four channels on the photopeak give $W(180°)/W(90°)=1.31\pm0.03$. A slight correction (plus 0.01 to both of the results above) has been included to account for the presence of a 920-kev component which contributed approximately five percent to the selected counts of the 770-kev coincidence photopeak. This component appears to have approximately the same intensity at angles 90° and 180° between the counters. Summing over the eight channels centered on the 770-kev photopeak it was found that $W(180°)/W(90°)=1.25\pm0.02$. In addition to the seven pairs of one-hour runs a pair of 9-hour runs was made during overnight periods. No attempt was made to analyze the upper and lower sides of the 770-kev peak separately due to the uncertainties in gain shifts over long periods. However, the eight channels covering the peak were summed giving $W(180°)/W(90°)=1.24\pm0.02$ for the pair of runs in good agreement with the corresponding experiment based on short runs.

TABLE I. (a) The experimental values of $W(180°)/W(90°)$ obtained from a measurement of the directional correlation of the 250–770 kev gamma-gamma cascade in U^{234}. Three portions of the composite 770-kev photopeak were selected for the measurement, the lower half-width at half-maximum counting rate, the upper half-width and the whole width consisting of both of these regions.
(b) The theoretically expected values are derived assuming that the measured coincidences are due to a mixture of two cascades, 250-751 kev and 250-795 kev with spin sequences $0^+(E1)1^-(E1)2^+$ and $0^+(E1)1^-(E1)0^+$, respectively. It is further assumed that the relative intensities of the two cascades are given by the branching expected theoretically from a spin 1^- and $K=0$ or 1 level to the spin 0^+ and 2^+ members of the ground-state rotational band.

		$W(180°)/W(90°)$		
		Lower half-width	Upper half-width	Whole width at half maximum counting rate
(a) Experiment	14 one-hr runs	1.19±0.03	1.31±0.03	1.25±0.02
	2 nine-hr runs	...	...	1.24±0.02
(b) Theory[a]	$K=0$	1.14	1.34	1.24
	$K=1$	1.42	1.65	1.54

[a] See reference 7.

INTERPRETATION OF THE ANGULAR CORRELATION RESULTS

We will begin by comparing the experimental results with what seems the most likely theoretical interpretation based on other experiments already summarized in the Introduction. Thus we assume the decay scheme given in Fig. 1. The first level in the 250-"770" kev gamma-gamma cascade is proposed at 1046 kev with spin and parity 0^+ and the second at 795 kev with spin and parity 1^-. Branching then occurs to the 2^+, 44-kev level and the 0^+ ground state. The three gamma rays are all assumed to have multipolarity $E1$. The observed directional correlation measured for the lower and upper parts of the 770-kev composite photopeak should differ since different superpositions of the two spin sequences $0^+-1^--2^+$ and $0^+-1^--0^+$ are involved in the two cases. Thus the results depend on the relative branching from the 795-kev 1^- level to the 44-kev 2^+ and ground state 0^+ levels and on the energy resolution of Counters B and C as well as on the directional correlations associated with the two spin sequences. Because the 751- and 795-kev components are not resolved in the scintillation coincidence spectrum, the branching ratio cannot be measured directly. However, since U^{234} lies

in the region of the strongly deformed nuclei the simple theoretical branching relations[7] are expected to be accurate. If the 795-kev level has spin 1^- and $K=0$, (the quantum number K[7] is the component of the total angular momentum I of the nucleus along the axis of symmetry of the nucleus) then the branching from this level to the ground-state rotational band is given by the intensity ratio $I(1^-\rightarrow 2^+)/I(1^-\rightarrow 0^+)=2(751/795)^3=1.69$ whereas if $K=1$, $I(1^-\rightarrow 2^+)/I(1^-\rightarrow 0^+)=0.5(751/795)^3=0.422$.

If the directional correlation function is expanded into Legendre polynomials $W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)$, then one expects from theory[8] $A_2=0.5$ and $A_4=0$ for the spin sequence $0^+(E1)1^-(E1)0^+$ and $A_2=0.05$ and $A_4=0$ for the spin sequence $0^+(E1)1^-(E1)2^+$. The corrections for the finite angular resolution of the counters reduce the two A_2 coefficients to 0.40 and 0.040, respectively.

Gaussian line shapes were plotted for the 751- and 795-kev components with the known linewidth for this energy of 10.5 percent and with the relative peak heights expected for the 90° and 180° positions of the counters. The relative peak heights of the two energy components were computed from the product of the theoretically known relative intensities and the directional correlation function $W(\theta)$ for the particular component and angle. On adding the 751- and 795-kev components so constructed at 90° and 180°, we get the actual line shapes expected at the two angles. For $K=0$, the total linewidths of the constructed peaks came out 12.9% and 13.3%, respectively, for 90° and 180°. The observed average composite photopeak widths for the seven pairs of runs were 13.5±0.4 for Counter B in the 90° position, 13.8±0.4 for Counter C in the 270° position, and 13.6±0.4 and 13.6±0.4, respectively, for Counters B and C at 180°. Thus the accuracy was not sufficient to observe the expected slight broadening of the line shape in going from 90°(270°) to 180°, but the observed widths do match fairly well the expected widths based on the analysis discussed above. Finally, the portions of the areas under the constructed composite curves corresponding to the channels summed over in the experimental case were determined. From these areas the expected values of $W(180°)/W(90°)$ were found for the various possibilities as given in Table I.

The possibility of $K=1$ appears to be ruled out decisively whereas the fit between theory and experiment for $K=0$ is good considering the nature of this comparison.

In addition to the directional correlation measurements incorporating the multichannel analyzer, another set of measurements was performed using only single-channel pulse-height selectors for making the energy selection. These measurements were made before it was realized that the 770-kev peak is a composite photopeak. Consequently, the position and width of the window selecting the 770-kev peak was not measured accurately and the results so obtained cannot be compared directly with the multichannel pulse-height analyzer results. However, the single-channel measurements were performed with an angle of 135° between the counters in addition to the angles 90° and 180°, so that information regarding the value of the directional correlation A_4 coefficient could be obtained. The results, without correcting for the finite angular resolution of the counters, are $W(180°)/W(90°)=1.20\pm0.02$ and $W(135°)/W(90°)=1.12\pm0.02$. It is seen that these results are consistent with the possibility $A_4=0$ proposed above.

To complete the analysis, it is of interest to compare the experimental results with predictions based on other spin assignments to the levels in question. It is readily seen that if the gamma rays are assumed to be of pure multipole order, no other interpretation of the experimental results can be found. If one considers the first transition to be a dipole-quadrupole mixture, then two additional composite spin sequences are possible. Both of these spin sequences still involve an intermediate spin and parity 1^- with $K=0$ and differ only in the initial spin. They are $[1(1,2)1^-(E1)0^+]+[1(1,2)1^-(E1)2^+]$ with δ_1, the ratio of the quadrupole to dipole reduced matrix elements[8] for the first gamma ray equal to approximately -1 and $[2(1,2)1^-(E1)0^+]+[2(1,2)1^-(E1)2^+]$ with $\delta_1=1.3$. As discussed in the Introduction, an upper limit has been placed on the K internal conversion coefficient of the 250-kev transition[4] which is reasonable only if the multipolarity of the 250-kev transition is $E1$. Thus the spin interpretations suggested above with the initial spin 1 or 2 appear to be unlikely since the first transition (250 kev) would have to be approximately a 50%-50% dipole-quadrupole mixture.

Gallagher and Thomas[9] have studied the $Np^{234}\rightarrow U^{234}$ K-capture decay and report evidence for a 1^- level at 788 kev in U^{234}. Evidently this level is the same as the one indicated at 795 kev in the present work. The measurements of Gallagher and Thomas were performed using a permanent magnetic spectrograph with 0.1% energy resolution and the level at 788 kev was established on the basis of energy sums and differences. The state was tentatively assigned $K=0^-$ and $I=1$, since the relative K-conversion intensities measured for the 744- and 788-kev transitions emitted from this state are in agreement with this assignment. Thus, $K=1$ is excluded for the state at 788 kev.

Evidence for 1^- levels have been reported for several nuclei neighboring U^{234} such as in Ra^{222}, Ra^{224}, Ra^{226},

[7] K. Alder, A. Bohr, T. Huus, B. Mottelson, and A. Winther, Revs. Modern Phys. 28, 541 (1956).
[8] L. C. Biedenharn and M. E. Rose, Rev. Modern Phys. 25, 729 (1953).
[9] C. J. Gallagher, Jr., and T. D. Thomas, University of California Radiation Laboratory Report UCRL-8864, August, 1959 (unpublished); Nuclear Phys. 14, 1–20 (1959/60).

Th^{226}, Th^{228}, and Pu^{238}.[7,10] Apparently such levels are to be interpreted as octupole vibrations of a nucleus about a spheroidal shape.[7] Building on the 0^+ ground state such octupole vibrations can give rise to excited bands with $K=0^-$, 1^-, 2^-, and 3^-. From the present experiments $K=0^-$ is indicated for the 795-kev level in U^{235} as discussed in the previous section. This is in accord with the studies of neighboring nuclei which also indicate $K=0^-$ for the 1^- level.[10] Thus, the 795-kev level should probably be interpreted as the lowest member of a $K=0^-$ rotational band. Population of the higher energy states with $I=3^-$, 5^-, etc., is not expected to be appreciable in the beta decay of Pa^{234} since on the basis of log *ft* values the ground-state spin of Pa^{234} appears most likely to be 0.

[10] F. Stephens, Jr., F. Asaro, and I. Perlman, Phys. Rev. **100**, 1543 (1955).

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Elastic Scattering of Heavy Ions by Gold and Bismuth*

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The angular distributions of C^{12}, N^{14}, O^{16}, and Ne^{20} elastically scattered by Au^{197} and Bi^{209} have been measured at laboratory energies of approximately 10.4 Mev per nucleon. The elastically scattered ions were recorded in photographic emulsions at laboratory angles from 19° to 175°. In general, measurements were extended only to angles where the ratio of the cross section to the Coulomb cross section, σ/σ_c, was greater than 0.1. In one case the measurement was extended to a region where $\sigma/\sigma_c \leq 1.4\times10^{-4}$. The cross sections all exhibited a behavior similar to that previously reported for C^{12} on Au^{197}. An oscillation in the cross-section ratio occurring at smaller angles than the 20% to 30% rise and sudden drop was observed. Excellent agreement was obtained with the Blair "sharp-cutoff" calculations for values of $\sigma/\sigma_c>0.2$. Nuclear interaction distances calculated by fitting the sharp-cutoff calculations are consistent with $r_0=1.46$ fermis, where $R=r_0(A_1^{\frac{1}{3}}+A_2^{\frac{1}{3}})$. No striking distinction can be made regarding the surface characteristics of the four projectiles or the two targets.

INTRODUCTION

THE study of elastic scattering of heavy ions from nuclei promises to be an important source of information concerning the size of nuclei and condition of the nuclear surface. The mean free path of nuclei heavier than α particles in nuclear matter is very small, so that the interaction is almost completely determined by the tails of the nuclear potentials and the Coulomb potential. The characteristic angular distribution obtained is best illustrated by the ratio of the measured cross section to the Coulomb cross section. It is found that at small angles this ratio is unity. As the angle increases, the ratio increases by about 20% to 30% and then falls rapidly. This same behavior was found for the elastic scattering of α particles from nuclei.[1]

A rather simple model of the interaction, the sharp-cutoff model,[2] has been applied with excellent results to the elastic scattering of nitrogen by nitrogen,[3] and carbon by gold.[4] The nitrogen-nitrogen results have been analyzed by Porter[5] using an optical model. He obtained good agreement with the experiment with a real nuclear potential of -40 Mev, an imaginary nuclear potential of -8 Mev, and a potential form factor of 6×10^{-14} cm. A good fit to the data could also be obtained by setting the real part of the nuclear phase shift equal to zero. Therefore, it is the absorption together with the Coulomb interaction which plays the major role in the elastic scattering, as would be expected because of the small mean free path in nuclear matter.

McIntyre *et al.*[6] have studied the elastic scattering

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[1] D. D. Kerlee, J. S. Blair, and G. W. Farwell, Phys. Rev. **107**, 1343 (1957).

[2] J. S. Blair, Phys. Rev. **95**, 1218 (1954); J. S. Blair, Phys. Rev. **108**, 827 (1957).

[3] H. L. Reynolds and A. Zucker, Phys. Rev. **102**, 1378 (1956).

[4] E. Goldberg and H. L. Reynolds, Phys. Rev. **112**, 1981 (1958).

[5] C. E. Porter, Phys. Rev. **112**, 1722 (1958).

[6] J. A. McIntyre, S. O. Baker, and T. L. Watts, Phys. Rev. **116**, 1212 (1960).