[4]L. Tisza, Phys. Z. Sowjetunion 11, 245 (1937).
[5]K. Huang, Phys. Rev. 102, 422 (1956).
[6]K. C. Richards and M. E. Rose, Phys. Letters 25B, 501 (1967).
[7]J. S. Greenberg and M. Deutsch, Phys. Rev. 102, 415 (1956).
[8]A. Ljubičić and B. A. Logan, Bull. Am. Phys. Soc. 17, 463 (1972).
[9]L. I. Schiff, Phys. Rev. 76, 89 (1949).
[10]M. E. Rose, Phys. Rev. 76, 678 (1949).
[11]C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (Wiley, New York, 1967).
[12]K. Adler, A. Bohr, T. Huus, B. Mottelson, and A. Winther, Rev. Mod. Phys. 28, 432 (1956).
[13]P. H. Stelson and F. K. McGowan, Phys. Rev. 99, 112 (1955).
[14]T. W. Bonner, A. A. Kraus, Jr., J. B. Marion, and J. P. Schiffer, Phys. Rev. 102, 1348 (1956); E. M. Tsenter, A. G. Khabakhpashev, and I. A. Pirkin, Zh. Eksperim. i Teor. Fiz. 37, 1133 (1959) [transl.: Soviet Phys.–JETP 10, 806 (1960)]; J. K. Bair and H. B. Willard, Phys. Rev. 128, 299 (1962); S. Gorodetsky, M. Port, J. Graff, J. M. Thirion, and C. Chouraqui, J. Phys. (Paris), 29, 271 (1968); J. G. Pronko, C. Rolfs, and H. Maier, Phys. Rev. 186, 1174 (1969).
[15]R. Wilson, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy* (see Ref. 1), p. 1557.
[16]S. A. Baranov, V. M. Kulakov, and V. M. Shatinsky, Nucl. Phys. 56, 252 (1964).
[17]See for example in M. A. Preston, *Physics of the Nucleus* (Addison-Wesley, Reading, Mass., 1962), p. 353.

PHYSICAL REVIEW C VOLUME 7, NUMBER 4 APRIL 1973

Atomic Masses of ^{232}Th, ^{235}U, and ^{238}U and a Mass Table for the Heavy Isotopes*

Rodney A. Britten† and Walter H. Johnson, Jr.
School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455
(Received 21 April 1972)

This paper reports the results of the authors' mass spectroscopic measurements on the masses of the isotopes ^{232}Th, ^{235}U, and ^{238}U. Notice is taken of recently reported mass-difference measurements and Q-value measurements, and a least-squares process is used to construct a new mass table for the heavy isotopes. This table differs from Wapstra's 1967 table in two major respects: (1) For most isotopes with $A > 220$ the new mass value is lower than the old mass value by 20–25 μu, or roughly $1\frac{1}{2}$ times the quoted error in the 1967 table. (2) As a result of the new measurements, the uncertainty in our knowledge of the masses of most of the heavy isotopes has been reduced by very roughly a factor of 3.

I. INTRODUCTION

Until recently the heaviest isotopes for which direct, high precision mass measurements were available were isotopes of bismuth and lead. In this paper the authors will present the results of their measurements on ^{232}Th, ^{235}U, and ^{238}U, the isotopes which head the natural-radioactive-decay series.

The authors' measurements on these isotopes were made using a 16-in. magnetic radius double-focusing Nier-Johnson mass spectrometer and the error-signal doublet-peak matching technique. The Minnesota mass-measuring instruments[1-3] and the error signal technique[4] have been described in some detail elsewhere. No further description will be given here. The equipment, when tuned, produced a full-width at half-maximum (FWHM) resolution of 150 000 to 200 000 for these measurements.

Two major problems were encountered in this work. One had to do with sample introduction, and the other was a calibration problem. The calibration problem arose from the fact that the measured values of known mass doublets were consistently too high by about 20 ppm. This consistent discrepancy was discovered by measuring three different types of doublets. Measured values of doublets of the type C_mH_{n+1}-C_mH_n were compared with the accepted value of the hydrogen mass. Measured values of $U^{35}Cl_{m_2}{}^{37}Cl_{n_2}$-$U^{35}Cl_{m_1}{}^{37}Cl_{n_1}$ type doublets were compared with the accepted value of the ^{37}Cl-^{35}Cl mass difference. Finally the sum of the measured values for the C_9H_{10}-$\frac{1}{2}{}^{235}$U and $\frac{1}{2}{}^{235}$U-C_9H_9 doublets was compared with the accepted hydrogen mass value. In all three cases the measured values were found to be too high by about 20 ppm. This calibration problem for the Minnesota instrument was ultimately resolved by applying a 20 ± 3-ppm correction to all doublet measurements. Other mass measurement laboratories have also had to apply corrections of this sort.

This calibration problem is somewhat similar to a problem encountered by Hudson[5] in 1969 when he used the Minnesota instrument to make measurements on the light rare-earth isotopes. He

found that measured values of hydrocarbon-hydrocarbon doublets agreed with the accepted hydrogen mass value to within 1 ppm, but closure errors indicated that measured values of metal-metal and metal-hydrocarbon doublets were too high by about 10 ppm. In the present work it was not possible to discern any difference between these three types of doublets. The cause of the earlier difficulty remains uncertain.

The sample problem arose from the fact that uranium and thorium are excellent getters. When heated, these elements and their salts tend to absorb large amounts of any hydrocarbon that is introduced into the instrument as a mass reference. The extent of the gettering depends somewhat on the hydrocarbon used. Eventually two workable doublets were found for each of the three isotopes to be measured.

In the case of ^{235}U the gettering problem, combined with the low natural abundance of this isotope, made it necessary to use an enriched sample. The Oak Ridge National Laboratories provided the ^{235}U enriched uranium in the form of U_3O_8, and it was converted into UCl_4 by means of the process described in U. S. patent number 2 688 529.

II. RESULTS

About half a dozen runs were made on each of the doublets listed in Table I. The mass of each of the isotopes ^{232}Th, ^{235}U, and ^{238}U was obtained by measuring two different doublets, and in each case the doublets gave answers that agree to within the limits of experimental error. Isotopic masses were calculated from the doublet values by employing the standard atomic masses of ^{1}H, ^{35}Cl, and ^{37}Cl listed in the 1964 Mass Table by Mattauch, Thiele, and Wapstra.[6] The errors quoted in Table I are the quadratic sum of the standard deviation of the mean, the uncertainty in calibrating resistors in a precision voltage divider, the uncertainty in the 20 ± 3-ppm correction, and the uncertainty in the 1964 Mass Table values for ^{1}H, ^{35}Cl, and ^{37}Cl. The final doublet errors correspond to about 1/1000 of the FWHM of the ion peak.

The doublet measurements listed in Table I include the 20 ± 3-ppm calibration correction. At this point it might be well to comment on the magnitude of that correction. The doublets involving ^{232}Th have widths of about 0.07 u. For such doublets a 20 ± 3-ppm correction amounts to about 1.5 μu with an uncertainty of about 0.3 μu. This uncertainty is rather small compared to the statistical fluctuation of the runs, and it contributes very little to the over-all doublet measurement error. If one takes a weighted average of the two ^{232}Th values, the doublet corrections tend to add. The over-all correction is

$$\alpha \frac{(\Delta m_1/\sigma_1^2 + \Delta m_2/\sigma_2^2)}{\frac{1}{2}(1/\sigma_1^2 + 1/\sigma_2^2)},$$

where α is the 20 ± 3-ppm correction factor, Δm_1 and Δm_2 are the measured doublet values, and σ_1 and σ_2 are the quoted uncertainties in the ^{232}Th values corresponding to Δm_1 and Δm_2. This over-all correction for ^{232}Th amounts to about 3 μu with an associated uncertainty of 0.4 μu. A similar treatment leads to similar results for the doublet measurements involving ^{238}U.

The case of ^{235}U is a bit different. From Table I one sees that the doublets involving ^{235}U have widths of about 0.5 u. For such doublets a 20 ± 3-ppm calibration correction amounts to about 10 μu with an associated uncertainty of about 1.5 μu. This uncertainty accounts for a good deal of the quoted error in the doublet measurements. When one takes a weighted average of the two ^{235}U measurements, however, one doublet correction tends

TABLE I. Doublet measurements in the present work.

Doublet	Reference hydrocarbon	No. runs	Δm (u)	Atomic mass (u) [a]
C_9H_8-$\frac{1}{2}$Th	Indene	6	0.043 571 2 ± 1.0	^{232}Th = 232.038 060 6 ± 2.4
$C_{12}H_8$-$\frac{1}{2}$Th ^{37}Cl ^{35}Cl	Biphenyl	5	0.076 196 7 ± 0.9	^{232}Th = 232.038 060 0 ± 2.8
$\frac{1}{2}$ ^{235}U-C_9H_9	α methylstyrene	4	0.451 533 6 ± 1.9	^{235}U = 235.043 920 6 ± 4.1
C_9H_{10}-$\frac{1}{2}$ ^{235}U	α methylstyrene	5	0.556 292 1 ± 2.4	^{235}U = 235.043 919 6 ± 5.1
C_9H_{11}-$\frac{1}{2}$ ^{238}U	Durene trimethylbenzene	10	0.060 683 0 ± 1.1	^{238}U = 238.050 788 2 ± 2.8
$C_{12}H_{10}$-$\frac{1}{2}$ ^{238}U $^{35}Cl_2$	Biphenyl	4	0.084 005 4 ± 0.7	^{238}U = 238.050 790 8 ± 3.1

[a] Isotopic masses were calculated from the doublet values by employing the standard atomic masses of ^{1}H, ^{35}Cl, and ^{37}Cl listed in the 1964 Mass Table by Mattauch, Thiele, and Wapstra (Ref. 6).

to be subtracted from the other. This pleasant result comes about because ^{235}U forms the upper member of one doublet and the lower member of the other. The over-all correction is

$$\alpha \frac{(\Delta m_1/\sigma_1^2 - \Delta m_2/\sigma_2^2)}{\frac{1}{2}(1/\sigma_1^2 + 1/\sigma_2^2)}.$$

Since the two terms in the numerator nearly cancel, this over-all correction amounts to only 0.1 μu and is negligible compared to the statistical spread of the runs.

At about the same time the present measurements were being made at the University of Minnesota, a somewhat similar set of measurements was being made at Harvard by Kerr and Bainbridge.[7] They obtained the following results:

^{238}U-^{206}Pb^{32}S = 0.104 253 9 u ± 10 μu (±3.7 μu);

^{235}U-^{206}PbC$_2$H$_5$ = 0.030 341 0 u ± 10 μu (±2.8 μu);

^{238}U-^{235}U = 3.006 858 6 u ± 10 μu (±6 μu);

^{206}PbH-^{207}Pb = 0.006 394 2 u ± 1.1 μu.

The 10-μu quoted errors represent limits of error. The errors listed in parentheses were computed on the "usual statistical basis." They include the uncertainty in a 30 ± 2-ppm calibration correction. It is these statistical errors which will be used for comparisons in this paper.

By using the ^{1}H and ^{32}S mass values from the 1964 Mass Table[6] one can cast these Harvard measurements in a somewhat more convenient form:

^{238}U-^{206}Pb = 32.076 327 6 u ± 3.8 μu;

^{235}U-^{206}Pb = 29.069 467 0 u ± 2.8 μu;

^{238}U-^{235}U = 3.006 858 6 u ± 6 μu;

^{207}Pb-^{206}Pb = 1.001 431 0 u ± 1.1 μu.

Other measurements of interest involve nuclear reaction Q-value measurements. Because the energy gained in a nuclear reaction is related to the mass lost by $E = mc^2$, nuclear reaction Q-value measurements are another method of measuring mass differences. Wapstra's 1967 Mass Table,[8] a revision of the heavy mass section of the 1964 table, lists a good many nuclear reaction Q-value measurements involving isotopes with $A > 229$. Table II lists some measurements[9-15] made since 1967. A least-squares adjustment of all these Q-value measurements gives the following isotopic mass difference values:

^{238}U-^{235}U = 3.006 873 1 u ± 4.4 μu;

^{235}U-^{232}Th = 3.005 868 3 u ± 4.3 μu.

Table III presents a comparison of various mass values. The 12 primary measurement values are

TABLE II. Some nuclear reaction Q-value measurements made since 1967 [Q (keV)].

Reference	Reaction	Q_{exp}	σ	Q_{1967}	σ	Δ [a]	σ_Δ	Δ/σ_Δ
9	^{217}At(α)^{213}Bi	7203.0	8	7199.3	3	3.7	9	0.44
	^{221}Fr(α)^{217}At	6455.0	5	6457.3	3	−2.3	6	−0.39
	^{225}Ac(α)^{221}Fr	5934.6	2	5931.3	3	3.3	4	0.93
10	^{228}Th(α)^{224}Ra	5516.8	1	5520.9	2	−4.1	2	−1.83
	^{232}U(α)^{228}Th	5413.6	1	5413.6	1	−0.0	1	−0.00
	^{233}U(α)^{229}Th	4907.9	1	4909.4	2	−1.5	2	−0.71
	^{238}Pu(α)^{234}U	5592.9	1	5592.1	1	0.8	1	0.57
	^{240}Pu(α)^{236}U	5255.3	1	5255.1	1	0.2	1	0.12
	^{242}Pu(α)^{238}U	4982.4	1	4980.8	3	1.6	4	0.43
11	^{226}Ac(β)^{226}Th	1105.0	10	1118.0	7	13.0	12	1.07
12	^{233}U(d, p)^{234}U	4656.0	15	4616.0	4	40.0	15	2.58
	^{235}U(d, t)^{234}U	935.0	15	950.3	4	−15.3	16	−0.98
13	^{239}Pu(t, p)^{241}Pu	3242.0	20	3285.0	4	−43.0	20	−2.11
	^{240}Pu(t, p)^{242}Pu	3043.0	20	3065.7	5	−22.7	21	−1.10
	^{242}Pu(t, p)^{244}Pu	2576.0	20	2570.2	11	5.8	23	0.26
	^{235}U(t, p)^{237}U	3178.0	20	3183.1	4	−5.1	20	−0.25
	^{236}U(t, p)^{238}U	2780.0	20	2791.4	5	−11.4	21	−0.55
	^{238}U(t, p)^{240}U	2253.0	20	2246.0	12	7.0	23	0.30
	^{232}Th(t, p)^{234}Th	2487.0	20	2485.5	7	1.5	21	0.07
14	^{239}Pu(n, γ)^{240}Pu	6533.7	2	6523.9	4	9.8	4	2.33
15	^{239}Pu(n, γ)^{240}Pu	6533.1	1	6523.9	4	9.2	4	2.41

[a] $\Delta = Q_{exp} - Q_{1967}$.

TABLE III. Comparison of mass values. The asterisk is used to designate primary measurements.

		Mass value (u ± μu)	Δ [a] (μu)	Δ/σ
^{238}U	Present Minn.	238.050 788 2 ± 2.8 [b]	−1.5	−0.54*
		238.050 790 8 ± 3.1 [c]	1.1	0.39*
	Harvard	238.050 795 6 ± 8.0	5.9	0.73
	1967 Table	238.050 819 1 ± 12.4	29.4	2.37
	Minn. LSQ.	238.050 789 7 ± 1.8	...	...
^{235}U	Present Minn.	235.043 920 6 ± 4.1 [d]	−3.8	−0.93*
		235.043 919 6 ± 5.1 [e]	−4.8	−0.94*
	Harvard	235.043 935 0 ± 7.5	10.6	1.41
	1967 Table	235.043 943 2 ± 11.5	18.8	1.63
	Minn. LSQ.	235.043 924 4 ± 2.1	...	...
^{232}Th	Present Minn.	232.038 060 6 ± 2.4 [f]	1.0	0.41*
		232.038 060 0 ± 2.8 [g]	0.4	0.14*
	1967 Table	232.038 079 3 ± 11.9	19.7	1.66
	Minn. LSQ.	232.038 059 6 ± 1.7	...	...
^{238}U-^{235}U	Nuclear reactions	3.006 873 1 ± 4.4	7.8	1.77*
	Harvard (direct)	3.006 858 6 ± 6.0	−6.7	−1.12*
	Harvard (indirect)	3.006 860 6 ± 4.7	−4.7	−1.00
	Present Minn. (wtd. ave.)	3.006 869 2 ± 3.8	3.9	1.03
	1967 Table	3.006 875 9 ± 5.4	10.6	1.96
	Minn. LSQ.	3.006 865 3 ± 2.2	...	...
^{235}U-^{232}Th	Nuclear reactions	3.005 868 3 ± 4.3	3.6	0.84*
	Present Minn. (wtd. ave.)	3.005 859 9 ± 3.7	−5.1	−1.38
	1967 Table	3.005 863 9 ± 4.7	−0.8	−0.17
	Minn. LSQ.	3.005 864 7 ± 2.4	...	...
^{238}U-^{206}Pb	Harvard	32.076 327 6 ± 3.8	−2.1	−0.55*
	Present Minn. (wtd. ave.)	32.076 321 4 ± 7.3	−8.3	−1.14
	1967 Table	32.076 352 5 ± 11.5	22.8	1.98
	Minn. LSQ.	32.076 329 7 ± 2.5	...	...
^{235}U-^{206}Pb	Harvard	29.069 467 0 ± 2.6	2.6	0.93*
	Present Minn. (wtd. ave.)	29.069 452 2 ± 2.8	−12.2	−1.58
	1967 Table	29.069 476 7 ± 10.4	12.3	1.18
	Minn. LSQ.	29.069 464 4 ± 2.2	...	...
^{207}Pb-^{206}Pb	Harvard	1.001 431 0 ± 1.1	−0.4	−0.36*
	1967 Table	1.001 436 5 ± 4.3	5.1	1.18
	Minn. LSQ.	1.001 431 4 ± 1.1	...	...

[a] Δ is the difference between the given mass value and the corresponding mass value in the Minnesota least-squares adjustment.

[b] From the doublet C_9H_{11}-$\frac{1}{2}{}^{238}U$.

[c] From the doublet $C_{12}H_{10}$-$\frac{1}{2}{}^{238}U\,{}^{35}Cl_2$.

[d] From the doublet $\frac{1}{2}{}^{235}U$-C_9H_9.

[e] From the doublet C_9H_{10}-$\frac{1}{2}{}^{235}U$.

[f] From the doublet C_9H_8-$\frac{1}{2}Th$.

[g] From the doublet $C_{12}H_8$-$\frac{1}{2}Th\,{}^{37}Cl{}^{35}Cl$.

designated by asterisks. The other values were derived from these. In cases where it was necessary to assume a value for ^{206}Pb to make a comparison, the value used was the value from the 1964 Mass Table.[6]

Probably the most stringent test of data agreement is the test of whether there exists a set of isotopic mass values which is in reasonably good agreement with all of the measurements. If such a set exists, it can be found through a least-squares adjustment process. In Table III the least-squares adjustment values are designated "Minn. LSQ.," and other values are compared to them. Note that for 10 of the 12 primary measurements there is agreement to within one σ. In only 1 of the 12 primary measurements is the disagree-

TABLE IV. Radioactive decay series.

Series	Reaction [a]	1967 Table Q_{exp} (keV)	1967 Table Δ [b]	1967 Table Δ/σ	1971 Minn. LSQ. Q_{exp} (keV)	1971 Minn. LSQ. Δ [b]	1971 Minn. LSQ. Δ/σ
$4n$	^{232}Th$(6\alpha+4\beta)^{208}$Pb	42 687.1 ± 22	14.8	0.67	42 683.8 ± 22	23.6	1.07
$4n+1$	^{229}Th$(5\alpha+2\beta)^{209}$Pb	35 071.0 ± 33	−31.8	−0.96	35 073.5 ± 33	−19.3	−0.58
$4n+2$	^{230}Th$(5\alpha+3\beta)^{210}$Bi	33 525.3 ± 25	−28.4	−1.14	33 525.3 ± 25	−15.0	−0.60
$4n+3$	^{231}Pa$(6\alpha+3\beta)^{207}$Pb	41 345.5 ± 11	5.3	0.48	41 345.5 ± 11	11.6	1.05

[a] The end points of the series are not the natural end points but rather the points of attachment to the top and bottom structures.

[b] Δ = experimental $Q-Q$ computed from mass table (1967 or Minn. LSQ.).

ment more than 1.5σ, and in no instance is it greater than 2.0σ. For the group of 12 primary measurements the rms value of Δ/σ is 0.85. In short, the data agreement is just about what one would expect on statistical grounds or perhaps a bit better.

The most serious disagreement seen in Table III is the disagreement with the 1967 table. One can understand how this disagreement comes about if one looks at the way in which the mass table was constructed. Nearly all input data for the 1967 Mass Table fall into three categories:
(1) A rather closely knit network of measurements linking isotopes with $A \geq 229$ (the top structure);
(2) a somewhat less closely knit network of measurements linking isotopes with $A \leq 210$ (the bottom structure); and
(3) four radioactive decay series linking the top and bottom structures.

From Table IV one can see a disturbing feature of the 1967 Mass Table: It places primary reliance on the $4n+3$ decay series. This series, with its 11-keV quoted error, is weighted 4 times as heavily as the $4n$ series, 5 times as heavily as the $4n+2$ series, and 9 times as heavily as the $4n+1$ series. Indeed the $4n+3$ series is weighted nearly twice as heavily as the other three series combined. The 1967 table for the high mass region lists more than 200 pieces of input data and uses these data to compute the masses of 97 isotopes with $A > 225$; yet in the last analysis the accuracy of these computed values depends largely on a single string of Q values being correct. On the basis of the new measurements it now appears that the Mass Table values for isotopes in the top structure were too high because the $4n+3$ decay chain was too long.

The six new measurements from Minnesota and two new measurements from Harvard provide eight precise and compatible links between the top and bottom structures. By continuing to think in terms of these structures one can get a fairly good idea of the effects of these new measurements.

First of all note that the new Harvard measurements have effectively short circuited the decay chains and have become the dominant influence in determining the separation of the top structure and the upper part of the bottom structure. In a least-squares adjustment these measurements, with their 3- and 4-μu quoted errors, are each weighted about 10 times as heavily as is the $4n+3$ series Q value. Table III shows that both of these links are shorter than predicted by the 1967 table. The ^{238}U-^{206}Pb link is shorter by 25 μu; the ^{235}U-^{206}Pb link is shorter by 10 μu. Taken together the Harvard measurements serve to bring the top and bottom structures about 15 μu closer together. Note also that members of the top structure do not move strictly in unison. The mass value for ^{238}U tends to fall more than the value for ^{235}U, and the two isotopic mass values come closer together.

The present Minnesota measurements of atomic masses introduce a new feature into the system, a set of six direct links between the top structure and "ground." From Table III one observes that these links are considerably shorter than the predictions of the 1967 table. For ^{238}U the differences are 31 and 28 μu; for ^{235}U they are 23 and 24 μu; for ^{232}Th they are 19 and 19 μu. Once again note the lack of complete rigidity in the top structure and note that the ^{238}U and ^{235}U values are brought closer together. Taken together the present Minnesota measurements serve to lower the top structure by about 23 μu. In accordance with what was said earlier, one expects that 15 μu of this change will be absorbed in the links between the top and bottom structures and that 8 μu of this downward change will be transmitted to the upper part of the bottom structure itself. Later when the authors present a complete tabulation of the Minnesota least-squares adjustment it will be seen that the changes wrought by the new measurements follow mainly this pattern. One noteworthy exception is provided by ^{207}Pb, the lowest member of the $4n+3$ decay series. Even though this decay series is no

longer a dominant influence in determining the separation of the top and bottom structures, it still retains enough rigidity to exercise a palpable influence on the bottom structure at the point of attachment. Thus as the top structure is lowered by 20 μu, the ^{207}Pb value is pushed down 12 μu instead of the usual 8 μu.

The principal effect of the nuclear reaction Q-value measurements listed in Table II is to alter relations within the top structure. In most cases the new measurements are in good agreement with the predictions of the 1967 table. In cases where there is disagreement, the quoted errors on the table values are usually substantially less than the quoted errors on the new measurements, so the new measurements have little influence on a new least-squares adjustment. The only exception to this rule is provided by the two new measurements of the ^{239}Pu(n,γ) reaction Q value. These new measurements by Chrien *et al.*[16] and Matussek *et al.*[17] are about 9.5 keV, or 2.4σ, higher than the prediction of the 1967 table and suggest that the true value of the ^{240}Pu-^{239}Pu mass difference is about 10 μu lower than the table value. Precisely measured α-decay Q values link ^{239}Pu and ^{240}Pu with ^{235}U and ^{236}U. A lessening of the ^{240}Pu-^{239}Pu mass difference leads to a corresponding reduction of the ^{236}U-^{235}U mass difference, and this effect in turn brings about a reduction of the ^{238}U-^{235}U mass difference. Among the Harvard measurements, the present Minnesota measurements, and the nuclear reaction Q-value measurements there seems to be unanimous agreement that the ^{238}U and ^{235}U mass values should be brought about 10 μu closer together.

The new (t,p) reaction Q-value measurements by Britt and Cramer[15] deserve further comment even though they do not bring about any major changes in a new least-squares adjustment. At the time the 1967 Heavy Isotope Mass Table was compiled three relevant (t,p) reaction Q values were available. These had been reported by Middleton and Marchant[18] in 1964. In making up the 1967 table Wapstra rejected the ^{236}U(t,p) Q value because it differed from a least-squares adjustment value of the other data by 110 keV, or $5\frac{1}{2}\sigma$. He kept the ^{235}U(t,p) value but probably regarded it with some suspicion because it was $2\frac{1}{4}\sigma$ away from the least-squares adjusted value. The ^{238}U(t,p) value looked good. Note in Table V that in all three cases the 1969 measurements by Britt and Cramer confirm the prediction of the table. Similar experimental confirmation of the table predictions may be seen in Baranov's remeasurement[12] of the ^{238}Pu and ^{240}Pu α-decay Q values.

TABLE V. (t,p) reaction Q values.

Reaction	Q (keV) 1964 Middleton and Marchant [a]	1967 Mass Table [b]	1969 Britt and Cramer [c]
^{235}U(t,p)	3138 ± 20	3183 ± 4	3178 ± 20
^{236}U(t,p)	2900 ± 20	2791 ± 5	2780 ± 20
^{238}U(t,p)	2242 ± 20	2246 ± 12	2253 ± 20

[a] See reference 18.
[b] See reference 8.
[c] See reference 15.

With that bit of advertisement for the least-squares process the authors now present in Table VI the Minnesota least-squares adjustment for isotopic masses in the high mass region. This adjustment incorporates all the new mass measurements and Q-value measurements listed in this paper together with all experimental results in this region listed by Wapstra[8] as input data for the 1967 Mass Table. No attempt has been made by the authors to assign their own laboratory weighting factors. The data which appeared as input in the 1967 Mass Table are given the same errors that Wapstra assigned them. New data are given the same errors assigned them in their original publication.

The 1964 Mass Table went astray in the high mass region because there were too few measured links between isotopes of different decay series and because one of the links that did exist was inaccurate. The multitude of links that were measured between 1964 and 1967 cured this problem. The 1967 table got into somewhat less serious trouble because it placed primary reliance on a single decay series. This difficulty has now been eliminated. The recent Minnesota and Harvard measurements provided eight precise and compatible links between the top and bottom structures and place our knowledge of isotopic masses in the high mass region on a considerably more secure foundation. An examination of Table VI shows that for most of the more than 100 isotopes with $A > 220$ the uncertainty in our knowledge of the isotopic mass has been reduced from roughly 12 μu to roughly 4 μu, about a factor of 3 improvement.

Note. Since the preparation of the present table, Wapstra and Gove have published a revision of the 1964 and 1967 Mass Tables. The 1971 Mass Table was published in Nucl. Data A9, 265 (1971). The 1971 Mass Table employed neither the present work nor the work of Kerr and Bainbridge.[7] Comparison of the 1971 Mass Table results with the earlier results indicates no important changes. The following table lists some selected masses

TABLE VI. The Minnesota least-squares adjustment.

Isotope	Minn. LSQ (u)	σ [a] (μu)	1967 Table [b] (u)	σ [a] (μu)	Δ [c] (μu)	Δ/σ [d]
Hg 206	205.977 508 9	22	···515 7	22	−7	−0.3
Tl 206	205.976 097 0	5.5	···103 7	7.5	−7	−0.9
Pb 206	205.974 460 0	2.5	···466 6	5.7	−7	−1.2
Bi 206	205.978 382 5	26	···389 1	26	−7	−0.2
Tl 207	206.977 429 6	6.0	···443 1	8.4	−14	−1.6
Pb 207	206.975 891 4	2.7	···903 1	6.1	−12	−1.9
Bi 207	206.978 472 3	9.0	···483 9	10	−12	−1.1
Po 207	206.981 593 1	14	···604 8	15	−12	−0.8
Tl 208	207.982 003 2	5.8	···010 6	7.5	−7	−1.0
Pb 208	207.976 642 2	3.6	···649 3	6.0	−7	−1.2
Bi 208	207.979 721 4	6.3	···730 2	7.7	−9	−1.1
Po 208	207.981 238 2	11	···242 4	12	−4	−0.4
Tl 209	208.985 341 5	17	···352 3	18	−11	−0.6
Pb 209	208.981 070 6	7.7	···079 9	9.0	−9	−1.0
Bi 209	208.980 384 3	4.4	···393 5	6.4	−9	−1.4
Po 209	208.982 420 5	11	···425 4	11	−5	−0.4
Tl 210	209.990 081 7	13	···093 5	14	−12	−0.8
Pb 210	209.984 183 0	3.1	···189 8	6.0	−7	−1.1
Bi 210	209.984 114 8	2.9	···121 6	5.9	−7	−1.2
Po 210	209.982 868 5	2.7	···875 1	5.8	−7	−1.1
At 210	209.987 030 4	26	···037 0	26	−7	−0.2
Pb 211	210.988 752 0	6.0	···769 0	11	−17	−1.6
Bi 211	210.987 278 8	6.1	···292 5	8.5	−14	−1.6
Po 211	210.986 645 1	3.5	···656 7	6.4	−12	−1.8
At 211	210.987 496 4	9.6	···508 0	11	−12	−1.1
Rn 211	210.990 601 1	14	···612 7	15	−12	−0.8
Pb 212	211.991 884 3	7.1	···892 1	8.5	−8	−0.9
Bi 212	211.991 268 9	5.9	···276 4	7.5	−7	−1.0
Po 212	211.988 857 9	3.7	···865 0	6.0	−7	−1.2
At 212	211.990 714 4	22	···723 2	23	−9	−0.4
Rn 212	211.990 702 5	13	···706 7	13	−4	−0.3
Bi 213	212.994 365 6	13	···376 4	14	−11	−0.8
Po 213	212.992 839 2	9.2	···848 8	10	−10	−0.9
At 213	212.993 057 4	210	···066 6	210	−9	−0.0
Rn 213	212.993 929 9	24	···934 8	24	−5	−0.2
Pb 214	213.999 823 2	5.8	···843 9	12	−21	−1.7
Bi 214	213.998 713 7	13	···725 5	14	−12	−0.8
Po 214	213.995 197 4	3.3	···204 2	6.1	−7	−1.1
At 214	213.996 325 2	11	···332 0	12	−7	−0.6
Fr 214	213.998 977 8	34	···984 4	34	−7	−0.2
Bi 215	215.001 835 9	100	···853 9	100	−18	−0.2
Po 215	214.999 432 2	5.8	···449 4	11	−17	−1.6
At 215	214.998 642 2	12	···655 9	14	−14	−1.0
Rn 215	214.998 674 1	110	···685 7	110	−12	−0.1
Fr 215	215.000 395 0	34	···406 6	34	−12	−0.3
Ra 215	215.002 753 6	26	···765 2	26	−12	−0.4
Po 216	216.001 900 4	7.3	···908 2	8.7	−8	−0.9
At 216	216.002 409 0	9.5	···416 5	11	−8	−0.7
Rn 216	216.000 265 3	11	···272 4	12	−7	−0.6
Ra 216	216.003 483 0	35	···487 2	35	−4	−0.1
At 217	217.004 698 0	13	···708 4	14	−10	−0.7
Rn 217	217.003 910 6	10	···920 2	11	−10	−0.9
Fr 217	217.004 742 9	300	···752 1	300	−9	−0.0
Ra 217	217.006 388 3	40	···393 2	40	−5	−0.1

TABLE VI *(Continued)*

Isotope	Minn. LSQ (u)	σ [a] (μu)	1967 Table [b] (u)	σ [a] (μu)	Δ [c] (μu)	Δ/σ [d]
Po 218	218.008 987 9	5.7	···008 6	12	−21	−1.7
At 218	218.008 697 5	14	···709 4	15	−12	−0.8
Rn 218	218.005 598 9	11	···605 7	12	−7	−0.6
Fr 218	218 007 513 6	15	···520 4	16	−7	−0.4
At 219	219.011 299 1	86	···317 1	87	−18	−0.2
Rn 219	219.009 490 2	5.6	···507 6	11	−17	−1.6
Fr 219	219.009 235 8	25	···249 5	25	−14	−0.5
Ra 219	219.010 037 4	150	···049 1	150	−12	−0.1
Rn 220	220.011 379 3	7.6	···387 2	8.9	−8	−0.9
Fr 220	220.012 310 2	12	···317 7	13	−7	−0.6
Ra 220	220.011 019 0	16	···026 0	16	−7	−0.4
Fr 221	221.014 232 6	14	···243 8	14	−11	−0.8
Ra 221	221.013 903 0	11	···912 6	12	−10	−0.8
Ac 221	221.015 666 1	370	···675 3	370	−9	−0.0
Rn 222	222.017 588 9	5.3	···609 7	12	−21	−1.7
Fr 222	222.017 540 6	29	···552 0	30	−11	−0.4
Ra 222	222.015 368 0	15	···374 9	16	−7	−0.4
Ac 222	222.017 772 3	19	···779 1	19	−7	−0.3
Fr 223	223.019 742 4	5.3	···760 4	11	−18	−1.6
Ra 223	223.018 509 3	5.4	···526 9	11	−18	−1.6
Ac 223	223.019 118 8	25	···132 5	26	−14	−0.5
Th 223	223.020 907 0	190	···918 6	190	−12	−0.1
Ra 224	224.020 195 3	7.8	···203 3	9.1	−8	−0.9
Ac 224	224.021 694 0	14	···701 4	15	−7	−0.5
Th 224	224.021 463 4	19	···470 4	20	−7	−0.4
Ra 225	225.023 609 9	6.8	···629 5	13	−20	−1.5
Ac 225	225.023 205 8	14	···214 5	15	−9	−0.6
Th 225	225.023 935 2	13	···944 8	13	−10	−0.7
Ra 226	226.025 417 4	4.9	···438 2	12	−21	−1.7
Ac 226	226.026 089 1	20	···100 6	21	−12	−0.5
Th 226	226.024 893 5	19	···900 3	20	−7	−0.3
Pa 226	226.027 875 3	22	···882 1	22	−7	−0.3
Ra 227	227.029 162 1	22	···180 1	24	−18	−0.7
Ac 227	227.027 755 7	4.8	···773 7	11	−18	−1.6
Th 227	227.027 708 9	5.1	···726 7	11	−18	−1.6
Pa 227	227.028 787 0	26	···800 7	27	−14	−0.5
Ra 228	228.031 076 6	5.5	···095 9	13	−19	−1.5
Ac 228	228.031 018 0	6.2	···037 1	13	−19	−1.5
Th 228	228.028 721 9	7.8	···733 4	9.3	−12	−1.2
Pa 228	228.030 982 2	15	···989 6	16	−7	−0.5
U 228	228.031 369 9	22	···377 0	22	−7	−0.3
Th 229	229.031 760 6	4.3	···780 4	12	−20	−1.6
Pa 229	229.032 073 2	15	···081 9	16	−9	−0.6
U 229	229.033 486 4	13	···496 0	14	−10	−0.7
Th 230	230.033 138 3	4.4	···159 2	12	−21	−1.8
Pa 230	230.034 530 0	20	···541 4	21	−11	−0.5
U 230	230.033 928 4	19	···935 3	20	−7	−0.4
Ac 231	231.038 553 4	110	···572 6	110	−19	−0.2
Th 231	231.036 299 0	3.1	···318 1	11	−19	−1.7
Pa 231	231.035 884 9	4.5	···903 1	11	−18	−1.6
U 231	231.036 270 3	54	···288 1	55	−18	−0.3
Np 231	231.038 260 9	60	···274 6	60	−14	−0.2
Th 232	232.038 059 6	1.7	···079 4	12	−20	−1.6

TABLE VI *(Continued)*

Isotope	Minn. LSQ (u)	σ [a] (μu)	1967 Table [b] (u)	σ [a] (μu)	Δ [c] (μu)	Δ/σ [d]
Pa 232	232.038 580 8	23	···592 3	23	−12	−0.5
U 232	232.037 136 9	7.9	···148 4	9.3	−11	−1.2
Pu 232	232.041 165 9	58	···173 0	58	−7	−0.1
Th 233	233.041 581 4	4.4	···603 7	12	−22	−1.8
Pa 233	233.040 244 9	3.8	···267 7	12	−23	−1.9
U 233	233.039 632 9	4.3	···654 1	12	−21	−1.8
Pu 233	233.042 977 5	25	···987 1	26	−10	−0.4
Th 234	234.043 607 3	5.2	···635 6	13	−28	−2.1
Pa 234	234.043 325 5	5.6	···353 6	13	−28	−2.1
U 234	234.040 954 3	4.3	···975 6	12	−21	−1.8
Np 234	234.042 886 7	17	···908 0	20	−21	−1.1
Pu 234	234.043 305 7	20	···312 6	20	−7	−0.3
Pa 235	235.045 427 3	110	···446 2	110	−19	−0.2
U 235	235.043 924 4	2.1	···943 2	11	−19	−1.6
Np 235	235.044 056 5	2.3	···075 4	11	−19	−1.6
Pu 235	235.045 271 8	63	···289 6	64	−18	−0.3
U 236	236.045 563 5	2.4	···591 3	12	−28	−2.4
Np 236	236.046 593 6	14	···605 1	15	−12	−0.8
Pu 236	236.046 037 5	9.6	···049 0	11	−11	−1.1
Pa 237	237.051 194 2	54	···219 7	55	−25	−0.5
U 237	237.048 725 0	3.5	···750 5	12	−26	−2.1
Np 237	237.048 169 9	3.3	···194 6	12	−25	−2.1
Pu 237	237.048 409 6	6.5	···434 1	13	−25	−1.9
U 238	238.050 789 7	1.8	···819 1	12	−29	−2.4
Np 238	238.050 949 2	9.0	···970 0	14	−21	−1.5
Pu 238	238.049 561 3	4.4	···582 2	12	−21	−1.8
Cm 238	238.053 026 5	38	···033 4	38	−7	−0.2
U 239	239.054 298 4	3.1	···327 3	13	−29	−2.3
Np 239	239.052 931 5	3.4	···951 0	12	−19	−1.7
Pu 239	239.052 156 2	2.2	···174 8	11	−19	−1.6
Am 239	239.053 023 7	22	···042 6	24	−19	−0.8
U 240	240.056 601 5	10	···632 4	17	−31	−1.8
Np 240	240.056 051 9	64	···079 9	65	−28	−0.4
Pu 240	240.053 808 1	2.3	···836 1	12	−28	−2.4
Cm 240	240.055 506 8	9.8	···518 3	11	−11	−1.0
Np 241	241.058 307 7	110	···332 6	110	−25	−0.2
Pu 241	241.056 847 6	3.2	···872 6	12	−25	−2.1
Am 241	241.056 825 5	3.2	···850 4	12	−25	−2.1
Cm 241	241.057 654 4	6.6	···679 0	13	−25	−1.9
Pu 242	242.058 741 7	2.1	···769 5	12	−28	−2.2
Am 242	242.059 551 9	9.0	···572 7	14	−21	−1.5
Cm 242	242.058 838 8	4.5	···859 6	12	−21	−1.7
Cf 242	242.063 659 9	39	···666 8	40	−7	−0.2
Pu 243	243.062 004 1	8.2	···030 7	15	−27	−1.8
Am 243	243.061 374 0	3.6	···393 5	12	−20	−1.7
Cm 243	243.061 380 8	2.9	···400 1	12	−19	−1.7
Bk 243	243.063 003 3	22	···022 2	25	−19	−0.8
Pu 244	244.064 204 6	9.7	···234 7	17	−30	−1.8
Am 244	244.064 281 8	3.3	···309 6	12	−28	−2.3
Cm 244	244.062 747 7	2.5	···7754	12	−28	−2.3
Cf 244	244.065 977 0	10	···988 5	11	−11	−1.0
Am 245	245.066 451 1	4.9	···476 5	13	−25	−2.0
Cm 245	245.065 485 3	3.5	···510 7	12	−25	−2.1

TABLE VI *(Continued)*

Isotope	Minn. LSQ (u)	σ [a] (μu)	1967 Table [b] (u)	σ [a] (μu)	Δ [c] (μu)	Δ/σ [d]
Bk 245	245.066 368 1	6.2	···393 0	13	−25	−1.9
Cf 245	245.068 046 2	6.9	···070 8	13	−25	−1.8
Pu 246	246.070 094 1	55	···121 5	56	−27	−0.5
Am 246	246.069 691 5	54	···718 9	55	−27	−0.5
Cm 246	246.067 222 3	3.5	···249 7	13	−27	−2.2
Cf 246	246.068 816 2	12	···837 0	16	−21	−1.3
Fm 246	246.075 248 8	45	···255 6	45	−7	−0.2
Cm 247	247.070 350 8	8.2	···379 4	15	−29	−1.9
Bk 247	247.070 268 2	32	···287 7	34	−20	−0.6
Es 247	247.073 604 4	39	···623 3	41	−19	−0.5
Cm 248	248.072 349 0	9.6	···378 7	16	−30	−1.8
Cf 248	248.072 189 4	32	···217 1	34	−28	−0.8
Fm 248	248.077 179 4	34	···190 9	34	−11	−0.3
Cm 249	249.075 954 8	11	···984 5	17	−30	−1.7
Bk 249	249.074 979 4	4.7	···004 8	13	−25	−2.0
Cf 249	249.074 844 3	4.5	···869 7	12	−25	−2.0
Es 249	249.076 357 4	33	···382 3	35	−25	−0.7
Bk 250	250.078 309 3	11	···336 7	16	−27	−1.7
Cf 250	250.076 404 2	6.4	···431 6	14	−27	−2.0
Fm 250	250.079 524 7	34	···545 5	36	−21	−0.6
Cf 251	251.079 561 7	13	···590 3	18	−29	−1.6
Es 251	251.079 946 1	46	···965 6	47	−20	−0.4
Cf 252	252.081 626 5	11	···656 2	17	−30	−1.7
Fm 252	252.082 471 7	39	···499 4	40	−28	−0.7
No 252	252.088 957 2	37	···968 7	38	−12	−0.3
Cf 253	253.085 114 6	54	···140 0	55	−25	−0.5
Es 253	253.084 824 8	7.1	···850 2	14	−25	−1.9
Es 254	254.088 025 8	12	···053 2	17	−27	−1.6
Fm 254	254.086 855 1	8.4	···882 5	15	−27	−1.9
No 254	254.090 968 6	38	···989 4	39	−21	−0.5
Fm 255	255.089 940 6	14	···969 2	19	−29	−1.5
Fm 256	256.091 701 6	34	···731 3	36	−30	−0.8
No 256	256.094 258 1	42	···285 8	44	−28	−0.6
Fm 257	257.095 086 7	54	···112 1	55	−25	−0.5

[a] Represents the rms deviation in μu for the associated mass.
[b] The dots indicate that the leading significant figures are omitted.
[c] Δ = mass value given in the Minnesota least-squares fit minus the mass value given in the 1967 Mass Table (in μu).
[d] Δ/σ represents the difference between the mass values from the Minnesota least-squares fit and the 1967 Mass Table divided by the error assigned to that mass in the 1967 Mass Table.

from the 1967 Mass Table compared with results from the 1971 Mass Table:

^{232}Th 1967 232.038 079 ± 12 u
1971 232.038 074 ± 11 u

^{235}U 1967 235.043 943 ± 11 u
1971 235.043 944 ± 11 u

^{238}U 1967 238.050 819 ± 12 u
1971 238.050 816 ± 11 u

When measured in terms of the magnitude of the disagreement between the Minnesota Mass Table and the 1967 Wapstra Mass Table, the revisions that have occurred in the new table by Wapstra and Gove are small. The disagreements referred to in the text of this paper, therefore, still exist.

*Work supported by Contract N00014-67-A-0013-0018 with the Office of Naval Research.

†Present address: The Perkin-Elmer Company, 2800 Metropolitan Place, Pomona, California 91766.

[1]R. R. Ries, R. A. Damerow, and W. H. Johnson, Jr., Phys. Rev. 132, 1662 (1963).

[2]E. G. Johnson and A. O. C. Nier, Phys. Rev. 91, 10 (1953).

[3]A. O. Nier, in *Nuclear Masses and Their Determination,* edited by H. Hintenberger (Pergamon, London, 1957), p. 185.

[4]J. L. Benson and W. H. Johnson, Jr., Phys. Rev. 141, 1112 (1966).

[5]M. C. Hudson, Ph.D. thesis, University of Minnesota, 1969 (unpublished).

[6]J. H. E. Mattauch, W. Thiele, and A. H. Wapstra, Nucl. Phys. 67, 1 (1965).

[7]D. Kerr and K. Bainbridge, Can. J. Phys. 49, 756 (1971).

[8]A. H. Wapstra, in *Proceedings of the Third International Conference on Atomic Masses,* edited by R. C. Barber (University of Manitoba Press, Winnipeg, Canada, 1968), p. 156.

[9]E. R. Cohen and J. W. M. Du Mond, in *Proceedings of the Second International Conference on Nuclidic Masses,* edited by W. H. Johnson (Springer-Verlag, New York, 1964), p. 152.

[10]B. N. Taylor, W. H. Parker, and D. N. Langenberg, Rev. Mod. Phys. 41, 375 (1969).

[11]B. S. Dzhelepov, R. B. Ivanov, M. A. Milhailova, L. N. Moskuin, O. M. Nazarenko, and V. P. Rodionov, Izv. Akad. Nauk SSSR Ser. Fiz. 31, 568 (1967) [transl.: Bull. Acad. Sci. USSR, Phys. Ser. 31, 563 (1967)].

[12]S. A. Baranov, Yadern. Fiz. 7, 727 (1968) [transl.: Soviet J. Nucl. Phys. 7, 442 (1968)].

[13]H. van Klugten and E. W. Koopman, Physica 40, 253 (1968).

[14]S. Bjornholm, J. Dubois, and B. Elbek, Nucl. Phys. A118, 241 (1968).

[15]H. C. Britt and J. D. Cramer, Phys. Rev. 185, 1553 (1969).

[16]R. E. Chrien *et al.*, Nucl. Data B4(No. 6), 577 (1970).

[17]P. Matussek *et al.*, Nucl. Data B4(No. 6), 577 (1970).

[18]R. Middleton and H. Marchant, in *Proceedings of the Second International Conference on Nuclidic Masses,* (see Ref. 9), p. 329.

PHYSICAL REVIEW C VOLUME 7, NUMBER 4 APRIL 1973

Nuclear Orientation Studies of the Decays of ^{187}W and ^{185,191,193}Os†

K. S. Krane* and W. A. Steyert

Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico 87544

(Received 22 December 1972)

Angular distributions have been measured for γ rays emitted following the decays of ^{187}W and ^{185,191,193}Os nuclei polarized at low temperatures in iron. The decay of polarized spin-1/2 nuclear levels was found to show isotropic angular distributions to three parts in 10^4, in keeping with angular momentum theory, and purity of the accepted nuclear spin values. The magnitudes of the magnetic moments of the ^{187}W and ^{193}Os ground states have been deduced to be $(0.688\pm0.021)\mu_N$ and $(1.30\pm0.19)\mu_N$, respectively, assuming saturation of the hyperfine field at the nucleus; the magnitude of the magnetic moment of the ^{191}Ir 171-keV level has been similarly deduced to be $(3.27\pm0.12)\mu_N$, based in part on the observation that the nuclear spin-lattice relaxation time associated with decays from that level is less than 0.1 sec. $E2/M1$ multipole mixing ratios have been deduced for a number of ^{187}Re and ^{193}Ir γ rays, and the multipole characters of several of the β radiations emitted by ^{187}W and ^{193}Os have been obtained; these multipolarities are discussed in terms of the nuclear structure. The use of polarized ^{191}Os as an absolute γ-ray anisotropy thermometer is discussed.

I. INTRODUCTION

The observation of the angular distribution of radiation emitted by nuclei polarized at low temperatures is a convenient means of investigating fundamental nuclear symmetries as well as of gathering data on nuclear properties such as spins, moments, and radiation multipolarities.[1] We report here an investigation into the γ rays emitted by ^{187}W and ^{185,191,193}Os polarized at $T\sim20$ mK in iron. The magnetic moments of the ^{187}W and ^{193}Os ground states and the 171-keV ^{191}Ir 5-sec excited state have been deduced from the observed angular distributions; the latter measurement was confirmed to be characteristic of the ^{191}Ir level rather than of the ^{191}Os parent by our observation that an upper limit of 0.1 sec can be set on the nuclear-spin-lattice relaxation time associated with decays from that level. Mixing ratios of a number of γ rays following the decays of the parent states have been deduced, and multipolarities of the unobserved β-radiation fields have been obtained.

In addition, angular distributions of γ rays from