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Ground-state β branching of gaseous fission products and their daughters for $A = 88$–91†

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The ground-state β branchings for several mass-separated Kr fission products and their daughters have been measured at the TRISTAN on-line separator facility at the Ames Laboratory Research Reactor. Absolute β counting was done with a 4π-geometry plastic scintillation detector and γ spectra were taken simultaneously with a Ge(Li) detector. The deduced values of the ground-state β branching β_{gs}, expressed as a percentage of decays, are: ^{88}Kr, 14±4; ^{88}Rb, 78.0±1.2; ^{89}Kr, 23±4; ^{89}Rb, 25±5; ^{90}Kr, 29±4; ^{90}Rb^g, 37±5; ^{91}Kr, 10±4; ^{91}Rb, 5±5.

[RADIOACTIVITY ^{88,89,90,91}Kr, ^{88,89,90,91}Rb [from ^{235}U(n,f)]; measured I_β, I_γ; Ge(Li) and 4π plastic scintillation detectors; deduced $\beta_{g.s.}$; mass-separated parent Kr activities.]

I. INTRODUCTION

As part of the systematic study of short-lived gaseous fission products and their daughters with the TRISTAN on-line mass separator facility, the ground-state β branching $\beta_{g.s.}$ has been measured for the decays of several Kr and Rb nuclides: ^{88}Kr, ^{88}Rb, ^{89}Kr, ^{89}Rb, ^{90}Kr, ^{90}Rb, ^{91}Kr, and ^{91}Rb. For each of the eight nuclides, detailed information was available on the γ-ray decay scheme, hence, $\beta_{g.s.}$ was determined by simultaneous measurements of absolute β-ray and γ-ray intensities using a plastic scintillation detector with 4π geometry for counting the number of β decays and a Ge(Li) detector for measuring the γ-ray spectrum. Mass-separated sources of ^{85}Kr^m, ^{87}Kr, and ^{138}Cs, for which $\beta_{g.s.}$ is known from previous work, were used to determine the absolute efficiency of the Ge(Li) detector.

The determination of $\beta_{g.s.}$ is necessary for the completion of the decay scheme of a nuclide since $\beta_{g.s.}$ must be known to determine the comparative half-life or logft value for each β-ray transition in the decay. In addition to their importance in nuclear structure studies, the values of $\beta_{g.s.}$, or the equivalent absolute decay rates, have relevance for the analysis and evaluation of radioactive decay heat rates from given fission-product inventories. To facilitate the use of the absolute decay rate information reported here, the results presented contain not only $\beta_{g.s.}$ but also the absolute decay intensity of the most intense γ ray for each of the eight decays.

II. EXPERIMENTAL PROCEDURE

The $\beta_{g.s.}$ measurements were made with mass-separated sources provided by the TRISTAN mass separator on line to the Ames Laboratory research reactor. Since a detailed description of the TRISTAN facility is available in the literature,[1] only brief mention of the features pertinent to the present work will be made here. A mass-separated ion beam of the Kr or Xe activity of interest was deposited on a tape in a moving tape collector (MTC). After the ion beam had been deposited for a selected time, the tape was moved to position the source on the tape in the center of the 4π plastic scintillation detector shown schematically in Fig. 1. After a preset delay, data were taken simultaneously with the 4π plastic and Ge(Li) detectors. The activity of interest, whether parent or daughter, was enhanced by proper selection of the beam deposit time, the delay time before data accumulation, and the data accumulation time. This sequence was repeated until sufficient data had been obtained.

The Ge(Li) detector used had an active volume of 60 cm^3 and a 2.5-keV resolution at 1.33 MeV. Since a part of the plastic scintillator and its light pipe, as well as the aluminum wall of the MTC chamber, were between the source and the Ge(Li) detector, it was necessary to determine the photopeak efficiency of the Ge(Li) detector while in the position shown in Fig. 1. Mass-separated sources of ^{85}Kr^m, ^{87}Kr, ^{138}Xe, and ^{138}Cs were used to determine the relative photopeak efficiency. As will

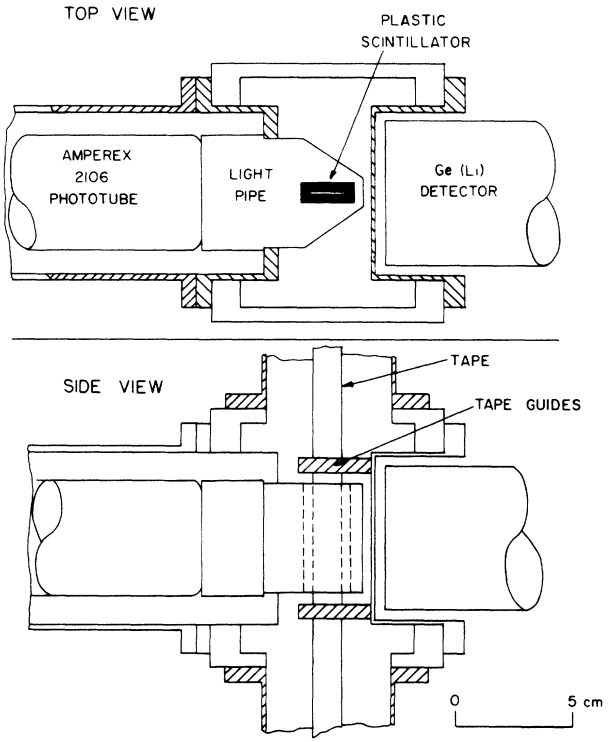

FIG. 1. Schematic diagram of the 4π plastic scintillator, Ge(Li) detector, and tape of MTC.

be discussed below, $^{85}Kr^{m}$, ^{87}Kr, and ^{138}Cs were used (with the 4π plastic scintillator β counts for source strength normalization) to obtain the absolute photopeak efficiency of the Ge(Li) detector.

The determination of absolute γ-ray intensities requires correction for dead-line losses in the Ge(Li) spectrometer electronics. The analog-to-digital converter (ADC) of the 8192-word multichannel analyzer provided the dead-time correction. As shown in the block diagram of Fig. 2, two crystal controlled timers were used to give a direct measure of the ADC live time. Both timers (as well as the β and γ counters) were enabled by a slow logic signal whenever the MTC was in the data accumulation mode. In addition, the live timer was enabled by a fast logic signal only when the ADC was not busy processing a signal. This method provided for accurate correction for the Ge(Li) dead-time losses, which were kept below 25% for all of the measurements reported here.

The plastic scintillation detector consists of a Pilot B plastic scintillator cemented to a light pipe which is optically coupled to an Amperex 2106 photomultiplier tube. The outer dimensions of the cross section shown in the top view of Fig. 1 are 8 mm by 22 mm with a slot 1.6 mm by 16 mm for the aluminized Mylar tape of the MTC to pass through. The tape guides shown in the side view of Fig. 1 have an opening of 0.2 mm by 13.1 mm, which together with the tension on the tape, prevent the tape from ever touching and contaminating the plastic scintillator. Since the length of the plastic scintillator is 41 mm, the solid angle subtended by a centered source is 99.4% of 4π.

The Amperex 2106 phototube was selected due to its fast time response, gain stability, and low noise characteristics when operated at bias voltages of 1500–1800 V. An ORTEC 9302 fast preamplifier and a Mechtronics 511 photon discriminator (fast amplifier and discriminator) were used with an ORTEC 772 fast counter (100 MHz) to register the β counts from the 4π β detector. An intense source of ^{137}Xe, which has a convenient half-life of 3.9 min, was used to determine directly the dead time of the β counter system by recording the count rate as a function of time while the source decayed. The computer fit to the resulting time response yielded a dead time of 5.1 nsec; hence, no corrections for dead-time counting losses were needed for counting rates lower than 2 MHz (this counting rate was never exceeded in the measurements reported here). The gain stability of the β counter was checked using a γ-ray source located outside the MTC vacuum chamber and was found to vary less than 0.5% over a 72-h interval.

Of critical importance for using the β counter in absolute decay rate measurements are count losses and extra counts (or double counting of β decays of the source). Double counting due to reflected fast pulse signals was investigated and eliminated by using a printed circuit board and shielded coaxial cables at the tube base as well as careful impedance matching to the fast preamplifier. Double counting due to transitions from excited levels of the daughter nucleus with lifetimes comparable to the β detector pulse width of 5 nsec can be corrected only in the data analysis. Such corrections are straightforward provided the

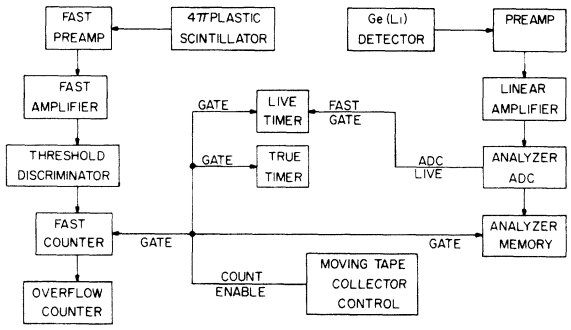

FIG. 2. Block diagram of the electronics used in the $\beta_{g.s.}$ study.

daughter level lifetime, delayed transition intensities, and internal conversion coefficients are known. The expressions for this correction are given in the data analysis discussion.

Count losses in the β counter due to dead-time effects were discussed above. Count losses due to a finite discriminator threshold level are of much greater significance since such losses are dependent upon the β-ray spectrum of the decaying source. Such count losses caused by too high a threshold setting would be greater for a low decay energy source such as $^{85}Kr^m$ with $Q_\beta = 0.686$ MeV than for higher decay energy sources such as ^{87}Kr with $Q_\beta = 3.888$ MeV or ^{138}Cs with $Q_\beta = 5.29$ MeV.[2-4] Although threshold losses can never be entirely eliminated because of finite electronic noise, they can be minimized to such a low level that they have a negligible effect on the accuracy of the determination of $\beta_{g.s.}$.

In the β counter described here, the threshold level is very low. As indicated in the discussion of the ^{91}Rb measurements, the threshold level is below 80 keV. A direct determination of the β-ray energy of the threshold would be extremely difficult due to the nonlinearity of the energy response of the thin plastic scintillator and the unavailability of monoenergetic electron sources of the desired energies and sizes needed to fit within the plastic scintillator. Six calibration measurements, two each with sources of $^{85}Kr^m$, ^{87}Kr, and ^{138}Cs, all yielded the same value (within a 4% root-mean-square deviation) for the absolute Ge(Li) efficiency normalization constant. This provided an indirect verification of the low threshold level since, as mentioned above, $^{85}Kr^m$ has a much lower decay energy than do the other two sources. Before the printed circuit board was used at the base of the phototube, however, $^{85}Kr^m$ sources gave a normalization constant that was only 75% of the value obtained with ^{87}Kr or ^{138}Cs. Use of the printed circuit board arrangement allowed the threshold level to be lowered by a factor of 50, which resulted in the virtual elimination of the dependence of the normalization constant upon the decay energy of the source. Since the Q_β values for the decays reported here are all 3 MeV or greater, any remaining threshold level effect was insignificant in the determination of the ground-state β branching for these decays.

III. DATA ANALYSIS

To outline the analysis used to deduce absolute decay rates, consider first the intensity relationships among β and γ intensities normalized to 100 β decays of the parent. Let β_i be the number of β decays to the excited state i, γ_{ij} be the number of γ transitions from state i to state j, and $N_{\gamma g.s.}$ be the total number of transitions from excited states to the ground state. With α_{ij} denoting the total internal conversion coefficient for the transition γ_{ij}, then

$$N_{\gamma g.s.} = \sum_i \gamma_{i0}(1+\alpha_{i0}) \tag{1}$$

and

$$100 - \beta_{g.s.} = \sum_i \beta_i = N_{\gamma g.s.} . \tag{2}$$

The arbitrarily normalized quantities γ'_{ij} and $N'_{\gamma g.s.}$ are used in the following expression for the determination of $\beta_{g.s.}$ from simultaneously measured β and γ intensities. The ratio $N'_{\gamma g.s.}/\gamma'_{ij}$, which is identical to $N_{\gamma g.s.}/\gamma_{ij}$, is assumed to be known from previous decay studies:

$$100 - \beta_{g.s.} = 100C(N'_{\gamma g.s.}/\gamma'_{ij})(I_{\gamma ij}/I_{\beta c}), \tag{3}$$

where C is the energy-independent normalization constant which converts relative photopeak intensities $I_{\gamma ij}$ into absolute γ intensities and $I_{\beta c}$ is the total number of decays of the parent counted by the 4π β counter. $I_{\gamma ij}$ includes the dead-time correction for the Ge(Li) ADC and the relative photopeak efficiency correction. Since count losses due to dead time and threshold level were negligible for the β counter, the only corrections needed to obtain $I_{\beta c}$ from the counts of the 4π β counter were for extra counts due to other activities in the source and double counts due to metastable levels.

Other activities in the source were mainly other members of the decay chain of the deposited Kr isotope but also included a small amount of activity of the next lower Kr mass chain since Kr hydride molecular ions were present in the deposited source.[1] The contaminants were identified from the Ge(Li) γ spectrum and the intensities of the identified contaminant γ peaks were used to determine the number of β counts to be subtracted from I_β, the observed β counts. The contaminant correction is best illustrated by example. Consider the case of the decay of ^{89}Kr with small contaminant activities of ^{89}Rb, ^{88}Kr, and ^{88}Rb, for which

$$(I'_\beta)_{^{89}Kr} = (I_\beta)_{^{89}Kr} - \frac{(I_{\gamma a})_{^{89}Kr}}{(I_{\gamma a}/I'_\beta)_{^{89}Rb}} - \frac{(I_{\gamma b})_{^{89}Kr}}{(I_{\gamma b}/I'_\beta)_{^{88}Kr}} - \frac{(I_{\gamma c})_{^{89}Kr}}{(I_{\gamma c}/I'_\beta)_{^{88}Rb}} . \tag{4}$$

The subscripts outside the parentheses identify the enhanced nuclide of the data set which yielded the data in the parentheses. The quantities $I_{\gamma a}$, $I_{\gamma b}$, and $I_{\gamma c}$ refer to the intensity of one (or more)

TABLE I. Determination of calibration constant C.

Decaying nucleus	MTC mode [a] (times in sec)	Contaminant activities	$N'_{\gamma g.s.}$ [b,c]	$\beta_{g.s.}$ [c]	C [d]
$^{85}Kr^{m}$	1200, 2, 1500	None	1046 ± 23	0	110 ± 5
	1200, 2, 260	None			103 ± 4
^{87}Kr	360, 2, 360	None	1400 ± 50	30.5 ± 2.2	109 ± 6
	30, 2, 30	None			104 ± 6
^{138}Cs	240, 7200, 1800	2.3% ^{138}Xe	1309 ± 21	0	112 ± 4

[a] Beam collect time, delay time after collection, and count time, respectively.
[b] Normalization is such that the strongest γ ray has an intensity of 1000.
[c] References for $N'_{\gamma g.s.}$ and $\beta_{g.s.}$ values are given in the text.
[d] Weighted average value of C is 107.7 with an rms error of 4.0.

γ rays in the decays of ^{89}Rb, ^{88}Kr, and ^{88}Rb, respectively. A similar expression for the enhanced run for ^{89}Rb also involves the unknown I'_β values for ^{89}Kr and ^{89}Rb. The two expressions are solved simultaneously to determine the desired I'_β values, which are the β counts after correction for contamination of other activities.

If the daughter nucleus has short-lived isomeric states, then a β decay which populates this state could be counted twice, once as a prompt β count and again as a count from the decay of the isomeric level. For an isomeric level of half-life τ and γ-decay intensity $I_{\gamma ij}$ with internal conversion coefficient α_{ij}, the corrected β counts $I_{\beta c}$ are given by

$$I_{\beta c} = I'_\beta - CI_{\gamma ij}(1 - e^{-ax} + \alpha_{ij})e^{-t/\tau}, \tag{5}$$

where a is the absorption coefficient of the γ ray in plastic of thickness x of 3 mm and t is the pulse pair resolving time of 10.2 nsec. The quantity $(1 - e^{-ax})$ is the probability that the photon is detected in the plastic scintillator and $e^{-t/\tau}$ is the probability that the two pulses are resolved and counted twice.

The right-hand side of Eq. (3) gives the number of β decays to excited states of the daughter per 100 β decays. The ratio $100(N'_{\gamma g.s.}/\gamma'_{ij})$, which requires knowledge of the level scheme of the daughter, converts the absolute count ratio $CI_{\gamma ij}/I_{\beta c}$ of the transition γ'_{ij} into the total number of excited-state β decays per 100 β decays. Rather than calculate $\beta_{g.s.}$ for each of the γ'_{ij} transitions selected in the analysis, one can calculate $\beta_{g.s.}$ from the average value of the ratio $I_{\gamma ij}/\gamma'_{ij}$ and its rms (root-mean-square) deviation which is typically 2–3%. Hence, Eq. (3) can be rearranged as

$$100 - \beta_{g.s.} = 100C(N'_{\gamma g.s.}/I_{\beta c})(I_{\gamma ij}/\gamma'_{ij})_{ave}. \tag{6}$$

The uncertainty in the difference $100 - \beta_{g.s.}$ is typically 5–6%, and is computed as the geometrical sum of the 3.7% rms uncertainty in C, a 1–3% uncertainty in $N_{\gamma g.s.}$, a 1–4% uncertainty in $I_{\beta c}$, and a 2–3% rms uncertainty in $(I_{\gamma ij}/\gamma'_{ij})_{ave}$. The uncertainty in $\beta_{g.s.}$ then depends on the size of $\beta_{g.s.}$ relative to 100, with values of $\beta_{g.s.}$ at the high end of the range having smaller relative uncertainties than values of $\beta_{g.s.}$ at the low end of the range.

Once $\beta_{g.s.}$ has been calculated from Eq. (6), the absolute intensity per 100 decays of any γ ray can be determined from the expression

$$\gamma_{ij} = (100 - \beta_{g.s.})(\gamma'_{ij}/N'_{\gamma g.s.}). \tag{7}$$

IV. RESULTS

The determinations of the calibration constant C and the results for $\beta_{g.s.}$ for the eight nuclei are summarized in Tables I and II, respectively. The times selected for the MTC were chosen to enhance as much as feasible the activity of interest in the decay chain of the Kr activity collected. (In this regard, the 70-cm distance between the beam deposition point and the β detector gave a minimum tape transport time of 1.8 sec, thus limiting the amount of parent enhancement possible.) The computer code ISOBAR[5] was used to determine optimum MTC times, without consideration of the simultaneous minimization of the hydride contaminants. The contaminant activities listed in Tables I and II were determined from the appropriate terms of the β count contaminant expression Eq. (4).

The normalization used for the values of $N'_{\gamma g.s.}$ in Tables I and II was such that the most intense γ ray in the decay had an intensity of 1000. In Table II the energy and absolute intensity (per 100 decays) of the most intense γ ray in each decay is given as determined from Eq. (7). References to the level schemes used for the values of $N'_{\gamma g.s.}$ and the γ rays used in the $\beta_{g.s.}$ determination are given in the following case by case discussions.

A. Calibration activities

The decay of $^{85}Kr^{m}$ ($T_{1/2} = 4.48$ h and $\beta_{g.s.} = 0$) has a 78.8% β branch to the 151-keV level of ^{85}Rb and a 21.2% isomeric branch (305-keV $M4$ transition with a total internal conversion coefficient of

TABLE II. Results of $\beta_{g.s.}$ measurements.

Decaying nucleus	MTC mode [a] (times in sec)	Contaminant activities	$N'_{\gamma g.s.}$ [c]	$\beta_{g.s.}$ [b] (logft) [d]	Most intense γ ray E_γ (keV)	I_{abs} [b]
^{88}Kr	150, 3, 150	6.3% ^{88}Rb 28.3% ^{87}Kr	2460 ± 30	14 ± 4 (9.34 ± 0.12)	2392.1	35.0 ± 1.8
^{88}Rb	240, 6000, 240	41.7% ^{88}Kr 9.1% ^{87}Kr	1029 ± 11	78.0 ± 1.2 (9.26 ± 0.01)	1836.0	21.4 ± 1.2
^{89}Kr	2.5, 2, 2.5	0.5% ^{89}Rb	3820 ± 80	23 ± 4 (7.01 ± 0.08)	220.9	20.1 ± 1.2
^{89}Rb	200, 1500, 1700	1.1% ^{89}Kr 4.6% ^{88}Kr 5.1% ^{88}Rb	1290 ± 60	25 ± 5 (7.48 ± 0.09)	1031.9	58 ± 5
^{90}Kr	2, 2, 2	1.1% ^{89}Rb 4.3% ^{89}Kr	1520 ± 30	29 ± 4 (5.91 ± 0.06)	1118.7	47 ± 3
^{90}Rb^g	50, 500, 550	1.2% ^{90}Kr 14.1% ^{89}Kr 29.8% ^{89}Rb	1120 ± 30	37 ± 5 (7.21 ± 0.06)	831.7	37 ± 3 [e]
^{91}Kr	2.5, 2, 2.5	5.3% ^{91}Rb 16.2% ^{90}Kr 2.5% ^{90}Rb	2100 ± 70	10 ± 4 [f] (6.44 ± 0.17)	108.8	42 ± 3
^{91}Rb	20, 100, 120	8.2% ^{90}Kr 29.4% ^{90}Rb	2970 ± 120	5 ± 5 [g] (7.45 ± 0.43)	93.6	32.0 ± 2.1

[a] Beam collect time, delay time after collection, and count time, respectively.
[b] Normalized to 100 decays.
[c] Normalized such that the most intense γ ray has an intensity of 1000; references in text.
[d] Logft values are calculated with a statistical β spectrum shape except for ^{88}Kr and ^{88}Rb, which are calculated with the first-forbidden unique β spectrum shape.
[e] Absolute intensity is for ^{90}Rb^g decay; the value for ^{90}Rb^m decay is 95 ± 5.
[f] Average of two independent measurements of 12 ± 5 and 8 ± 5; see text for discussion.
[g] Obtained by relative γ-ray intensity measurement with ^{91}Sr; see text for discussion.

0.509).[2,6] Assuming all of the electrons and 3% of the γ rays of the 304-keV transition are detected by the β detector, one obtains the relation $I_{\beta c} = 0.912 I'_\beta$. There were no contaminants in either of the two runs (one at the beginning and one at the end of the series of $\beta_{g.s.}$ measurements). The value of $N'_{\gamma g.s.}$ and the intensities of the two γ rays were obtained from Ref. 2. Both γ rays were used to determine $(I_{\gamma ij}/\gamma'_{ij})_{ave}$ with an uncertainty of 3.9% and 3.0%, respectively, for the two runs. The constant C was computed from Eq. (6).

The two runs of ^{87}Kr ($T_{1/2} = 76.4$ min and $\beta_{g.s.} = 30.5 \pm 2.2$)[3] had no contaminants and, as was the case for ^{85}Kr^m, bracketed the series of measurements. The level scheme of Shihab-Eldin *et al.*[7] was used for the γ-ray intensities and to obtain $N'_{\gamma g.s.}$. Seven γ rays (at 403, 674, 846, 1176, 1338, 1740, and 2012 keV) provided an $(I_{\gamma ij}/\gamma'_{ij})_{ave}$ value with an rms uncertainty of 3.2% and 2.4%, respectively, for the two runs.

The level scheme of Carlson, Talbert, and McConnell[4] was used for the decay of ^{138}Cs ($T_{1/2} = 32.2$ min and $\beta_{g.s.} = 0$). Seven γ rays (at 228, 463, 547, 872, 1010, 1436, and 2218 keV) gave a $(I_{\gamma ij}/\gamma'_{ij})_{ave}$ with a 1.6% rms uncertainty. The ^{138}Xe ($T_{1/2} = 14.2$ min) contaminant was minimized by the 2.5-h delay before counting.

The weighted average of the five determinations of C is 107.7 with an rms uncertainty of 4.0. This average value was used in the calculations of $\beta_{g.s.}$ for the eight decays listed in Table II.

B. ^{88}Kr decay

The decay of 2.84-h ^{88}Kr into ^{88}Rb is complicated (from the point of view of isobaric enhancement via an MTC) by the 17.8-min half-life of the daughter ^{88}Rb. The enhancement of ^{88}Kr over ^{88}Rb was obtained at the cost of appreciable ^{87}Kr contamination; 65.4% of the β counts were from the ^{88}Kr decay. The I'_β value had an uncertainty of 2.6% due to the contaminant correction of Eq. (4). Six ^{88}Kr γ rays (at 196, 362, 835, 1518, 1530, and 2196 keV) provided a value of $(I_{\gamma ij}/\gamma'_{ij})_{ave}$ with a 2.0% rms uncertainty. The level scheme of Bunting *et al.*[8] was used for the γ-ray intensities and for $N'_{\gamma g.s.}$. The value of $\beta_{g.s.}$ obtained, 14 ± 4, is in excellent agreement with the value of 14 ± 4 derived from systematics by Martin.[6]

C. ^{88}Rb decay

The ^{88}Rb run had secular equilibrium of ^{88}Rb with its longer-lived ^{88}Kr parent. As a result, the enhancement of ^{88}Rb was only 49.2%. The ^{88}Rb I'_β value had an uncertainty of 3.5%. The two γ rays

at 898 and 1836 keV (the only ^{88}Rb γ rays well separated from ^{88}Kr and ^{87}Kr γ rays) provided a value of $(I_{\gamma ij}/\gamma'_{ij})_{ave}$ with an uncertainty of 2.5%. The level scheme of Bunting *et al.*[8] was used for the γ-ray intensities and for $N'_{\gamma g.s.}$. The $\beta_{g.s.}$ value obtained, 78.0 ± 1.2, is in excellent agreement with the 76.2 ± 1.1 value of Ragaini and Knight[9] and the 75.4 ± 2.5 value of Halbig and Wohn[10] from a $\pi\sqrt{2}$ magnetic spectrometer measurement.

D. ^{89}Kr decay

A 99.5% enhancement of ^{89}Kr was obtained, resulting in an I'_β value with an uncertainty of less than 0.1%. Fourteen γ rays (at 221, 345, 356, 365, 369, 577, 586, 827, 1103, 1107, 1236, 1324, 1692, and 1694 keV) gave a value of $(I_{\gamma ij}/\gamma'_{ij})_{ave}$ with a 3.9% rms uncertainty. The level scheme of Henry, Talbert, and McConnell[11] was used for the γ-ray intensities and for $N'_{\gamma g.s.}$. The resulting value of 23 ± 4 for $\beta_{g.s.}$ disagrees sharply with the value of 0.1 reported by Kitching and Johns[12] in a study of the ^{89}Kr decay using chemically separated sources. However, Henry, Talbert, and McConnell deduced a $\beta_{g.s.}$ of 14 ± 2 for the ^{89}Kr decay from a relative γ-ray intensity measurement in an equilibrium source of ^{89}Kr-^{89}Rb; in this determination they used the $\beta_{g.s.}$ value of 18 reported by Kitching and Johns[13] for the decay of ^{89}Rb. As discussed by Henry, Talbert, and McConnell, the 0.1 value for $\beta_{g.s.}$ and the value of 4 for the branching to the 220-keV level reported by Kitching and Johns[12] are inconsistent with the more complete decay scheme of Henry, Talbert, and McConnell and with the Q_β value determined by Clifford *et al.*[14] from γ-gated β spectra. The $\beta_{g.s.}$ value reported here is consistent with the logft value normally expected for a first-forbidden nonunique β transition, which is the expected character of the ground-state β group in the decay of ^{89}Kr.[11]

E. ^{89}Rb decay

Although the ^{89}Rb data had only a 1.1% ^{89}Kr contamination, the very large number of ^{89}Kr γ rays limited the number of well-separated ^{89}Rb γ rays of adequate intensity to four (at 658, 948, 1032, and 1248 keV) The I'_β value had a 0.7% uncertainty and the $(I_{\gamma ij}/\gamma'_{ij})_{ave}$ value had a 3.0% rms uncertainty. The level scheme of Henry, Talbert, and McConnell[11] was used for $N'_{\gamma g.s.}$ and the γ-ray intensities. Our resulting value of 25 ± 5 is larger than the value of 7 ± 5 reported in 1956 by O'Kelley, Lazar, and Eichler[15] and the value of 18 reported by Kitching and Johns[13] for β-γ coincidence measurements with a magnetic spectrometer. Part of the difference between the latter value of 18 (with no uncertainty) and our value of 25 ± 5 is probably due to differences in the two level schemes used. It should also be noted that the value of 14 ± 2 deduced by Henry, Talbert, and McConnell for the ^{89}Kr decay (and based on Kitching and Johns $\beta_{g.s.}$ value of 18 for the ^{89}Rb decay) would increase to stand in excellent agreement with our direct determination of 23 ± 4 had they used our ^{89}Rb $\beta_{g.s.}$ value of 25 ± 5.

F. ^{90}Kr decay

The ^{90}Kr data were analyzed using the unpublished level scheme of Duke and Talbert,[16] which has been tentatively adopted in the $A = 90$ compilation of Kocher,[17] rather than the less complete decay scheme of Mason and Johns.[18] Five γ rays (at 234, 242, 539, 554, and 1118 keV) provided a value of $(I_{\gamma ij}/\gamma'_{ij})_{ave}$ with a 3.9% rms uncertainty. (As was the case with the ^{89}Rb data, the choice of suitable ^{90}Kr γ rays was restricted due to the prolific number of ^{89}Kr γ rays present in the ^{90}Kr data.) The I'_β value had an uncertainty of only 0.4%. The ^{90}Rb contaminant consisted only of the 153-sec ground-state activity since a negligible amount of the 258-sec isomeric activity was present; thus no correction had to be made for the 106-keV isomeric transition. Our resulting $\beta_{g.s.}$ value of 29 ± 4 disagrees with the value of 10 reported by Mason and Johns, whose indirect value was deduced from a β-γ coincidence probability for the 540-keV γ ray. The incorrect double placement of this γ ray in the level scheme of Mason and Johns can, according to Duke and Talbert, account for much of the difference between our value of 29 ± 4 and the Mason and Johns value of 10. A $\beta_{g.s.}$ value of 27 ± 5, based on a preliminary calculation of our ^{90}Kr data, was adopted by Kocher in the $A = 90$ compilation[17]; the value of 29 ± 4 in Table II is a final calculation from the same data.

G. ^{90}Rb decay

As was the case with the ^{90}Kr decay, the ^{90}Rb decay was analyzed using the unpublished data of Duke and Talbert.[16] Some of these data have been tentatively adopted by Kocher in the $A = 90$ compilation.[17] In addition, our determination of $\beta_{g.s.}$ for the ^{90}Rb decay also made use of more recent data of Duke and Talbert that were not available at the time of the $A = 90$ compilation. Six γ rays (at 832, 1061, 1375, 1377, 1666, and 2128 keV) were used to give an $(I_{\gamma ij}/\gamma'_{ij})_{ave}$ value with an rms uncertainty of 4.2%. The I'_β value had an uncertainty of 3.2% due to the corrections required for the ^{89}Kr and ^{89}Rb contaminants.

The analysis of the ^{90}Rb decay is complicated by the existence of the 258-sec isomeric level of ^{90}Rb at 106.9 keV. Since the isomer is longer lived than the 153-sec ^{90}Rb ground state, the isomer is en-

hanced relative to the ground state in any source produced by delaying after a collection of ^{90}Kr. For the ^{90}Rb data given in Ref. 17, the isomer activity was enhanced relative to equilibrium activity by a factor of 1.65 over the ground-state activity. For the ^{90}Rb data of the present work, which was performed with different MTC time conditions, the relative enhancement factor was 1.96. Thus in the present work the contribution from the isomer to the intensity of any of the six γ rays used in the analysis was greater by 19% than the contribution from the ground state when comparing the intensities of the present work with those of Ref. 17. Since the actual effect on any γ ray depends upon the relative population of that γ ray by the two activities, a complete analysis requires knowledge of the separate decay schemes of ^{90}Rb^m and ^{90}Rb^g.

In the work of Mason and Johns,[18] the assumption was made that levels in ^{90}Sr were fed by β decay either by the decay of ^{90}Rb^g or by the decay of ^{90}Rb^m. Then analyses of γ-ray intensities from separate sources taken under different time conditions were used to propose separate decay schemes for ^{90}Rb^m and ^{90}Rb^g. These decay schemes, in which $16 \pm 3\%$ of the ^{90}Rb β decays originate in the isomer, are consistent with their decay scheme for ^{90}Kr, in which $12 \pm 2\%$ of the ^{90}Kr decays lead to the isomer, $86 \pm 2\%$ lead to the ground state, and 2% are unclassified. This information is in excellent agreement with the ^{90}Kr decay scheme of Duke and Talbert[16] in which 12.4% of the ^{90}Kr decays lead to the isomer. In this latter work, however, separate decay schemes for ^{90}Rb^g and ^{90}Rb^m have not yet been determined due to the greater number of γ rays and ^{90}Sr levels involved in the decay of ^{90}Rb. At the present time there are data under analysis by Talbert, Duke, and Wohn[19] which should lead to separate decay schemes for ^{90}Rb^m and ^{90}Rb^g that are more complete than those proposed by Mason and Johns. (The data under analysis include γ-ray spectra for $A = 90$ equilibrium sources and strongly isomer-enhanced sources, as well as γ-ray spectrum multiscaling data.)

Values of $\beta_{g.s.}$ for ^{90}Rb^g were deduced from the present ^{90}Rb data for different assumed decay schemes for ^{90}Rb^m. These different ^{90}Rb^m decay schemes included one which had the same ^{90}Sr levels fed by β decay from the isomer as from Mason and Johns; schemes which differed significantly from that of Mason and Johns were also used. Schemes with significant differences were proposed primarily to explore the sensitivity of the resultant $\beta_{g.s.}$ value of ^{90}Rb^g to the choice of ^{90}Rb^m decay scheme. The exploration showed very little sensitivity to the particular scheme used to deduce $\beta_{g.s.}$. The lack of sensitivity can be partly understood upon inspection of Eq (6). Both $N'_{\gamma g.s.}$ and $I_{\beta c}$ are reduced in nearly the same manner when the decay intensity of ^{90}Rb^m is increased. Also the ratio $(I_{\gamma ij}/\gamma'_{ij})_{ave}$ is virtually unaffected by the changes in the ^{90}Rb^m decay intensity.

The $\beta^g_{g.s.}$ value of 37 ± 5 for ^{90}Rb^g given in Table II was deduced using level schemes for ^{90}Rb^g with $N'_{\gamma g.s.} = 1120 \pm 30$ and ^{90}Rb^m with $N'_{\gamma g.s.} = 420 \pm 40$ for the time conditions of the measurement. With the schemes used the percent isomeric contributions to the six γ rays used in the $\beta_{g.s.}$ analysis were 38%, 8%, 87%, 100%, 71%, and 100%, respectively, for the 832-, 1061-, 1375-, 1377-, 1666-, and 2128-keV γ rays. These percentages of the γ-ray intensities $I_{\gamma ij}$ were used in deducing an $(I_{\gamma ij}/\gamma'_{ij})_{ave}$ value with a 4.2% rms uncertainty. The $I_{\beta c}$ value was obtained by subtracting from I'_β the contribution due to ^{90}Rb^m, which was calculated using Eq. (6) for ^{90}Rb^m with $\beta^m_{g.s.} = 0$. The resultant $I^m_{\beta c}$ value was 19% of I'_β (the total measured ^{90}Rb β counts) and gave an $I^g_{\beta c}$ value with an uncertainty of 4.0%.

The analysis described in the preceding paragraph which yielded $\beta^g_{g.s.}$ of 37 ± 5 was done using the choice of schemes for ^{90}Rb^g and ^{90}Rb^m which most closely agreed with the (as yet incompletely analyzed) data of Talbert, Duke, and Wohn.[19] The uncertainty of ± 5 spans the range of values of $\beta^g_{g.s.}$ obtained for other choices of ^{90}Rb^m and ^{90}Rb^g schemes. The most extreme choice (maximum isomer strength) consistent with the data[19] yielded a $\beta^g_{g.s.}$ value of 42 ± 6. The minimum $\beta^g_{g.s.}$ value of 32 ± 7 was obtained by ignoring the isomer entirely and using directly the γ-ray intensities of Ref. 17; the larger uncertainty in this minimum value of $\beta_{g.s.}$ is due to the larger rms uncertainty of 8% in $(I_{\gamma ij}/\gamma'_{ij})_{ave}$ obtained when the existence of the isomer is ignored. The $\beta^g_{g.s.}$ value of 37 ± 5 reported here differs negligibly from the preliminary $\beta^g_{g.s.}$ value of 36 ± 6 included by Kocher[17] in the $A = 90$ compilation. The value of $\beta^g_{g.s.}$ reported here may change slightly when a final choice for the ^{90}Rb^m and ^{90}Rb^g decay schemes is made from the data[19] under analysis, but the change is expected to be small in comparison to the uncertainty of ± 5; thus the $\beta^g_{g.s.}$ value of 37 ± 5 reported here can be regarded as the final value.

The ^{90}Rb^g $\beta_{g.s.}$ value of 37 ± 5 differs appreciably from the value of 15 deduced by Mason and Johns[18] from their level scheme and the β-γ measurment of Johnson, O'Kelley, and Eichler[20] which indicated that the intensity of the 832-keV γ ray is 56% of the total β intensity of ^{90}Rb. The statement was made in Ref. 18 that this 56% value is relatively insensitive to the time at which the measurement was made since the isomer is a relatively small fraction of the total β intensity. On the contrary,

the time of the measurement is quite significant since virtually all of the isomer decay cascades through the 832-keV transition, whereas only about 40% of the ground-state decay cascades through this transition. For the particular decay schemes used in our analysis, the intensity of the 832-keV γ ray is 37% of the ^{90}Rb^{g} decay and 95% of the isomer decay. Since the isomer is the longer lived of the two activities, any value greater than about 40% could be obtained for the 832-keV γ-ray intensity relative to the total ^{90}Rb β intensity, depending on the time conditions for the ^{90}Rb source. (For instance, from the time intervals for our ^{90}Rb measurement and with our $\beta^{g}_{g.s.}$ value of 37, the 832-keV γ-ray intensity is 48% of the total ^{90}Rb β intensity.) The difference between our $\beta^{g}_{g.s.}$ value of 37 and the Mason and Johns value of 15 can be accounted for if one takes into consideration the unreported time conditions for the β-γ measurement used by Mason and Johns and the more complete level schemes used in our determination of $\beta^{g}_{g.s.}$.

H. ^{91}Kr decay

The ^{91}Kr data were analyzed using the level scheme of Glascock, Talbert, and Duke[21] Eight γ rays (at 502, 507, 613, 1102, 1109, 1501, 1502, and 1506 keV) provided a value of $(I_{\gamma ij}/\gamma'_{ij})_{ave}$ with a 3.2% rms uncertainty. The I'_{β} value had a 1.2% uncertainty due to corrections for contaminants of ^{91}Rb, ^{90}Kr, and ^{90}Rb. Reference 21 was used for the γ-ray intensities and for $N'_{\gamma g.s.}$. Our resulting $\beta_{g.s.}$ value is 12 ± 5. This result is in very good agreement with the $\beta_{g.s.}$ value of 8 ± 5 determined by Glascock, Talbert, and Duke on the basis of the relative γ-ray intensities for ^{91}Kr, ^{91}Rb, and ^{91}Sr. (In the latter determination γ-ray spectra were taken with ^{91}Kr and ^{91}Rb in equilibrium with the ion beam and then again a few hours after the ^{91}Kr deposition was halted in order to obtain ^{91}Sr γ-ray spectra; the known[22] value of $\beta_{g.s.}$ for ^{91}Sr was then used to calculate $\beta_{g.s.}$ for ^{91}Kr and ^{91}Rb.) The $\beta_{g.s.}$ value of 10 ± 4 given in Table II is the weighted average of the two independent determinations made with the TRISTAN facility. Our $\beta_{g.s.}$ value of 10 ± 4 is in sharp disagreement with the value of 20 ± 2 reported by Achterberg *et al.*[23] The disagreement could be due to differences in relative γ-ray transition intensities and the presence of the many additional transitions reported in Ref. 21.

I. ^{91}Rb decay

The ^{91}Rb data had negligible ^{91}Kr contamination, but did have appreciable ^{90}Kr and ^{90}Rb contamination, as indicated in Table II. Four ^{91}Rb γ rays (at 345, 439, 603, and 1137 keV) were used to give a value of $(I_{\gamma ij}/\gamma'_{ij})_{ave}$ with a 3.1% rms uncertainty. The most intense transition at 93.6 keV was not used because the relative photopeak efficiency was not determined with sufficient accuracy at this low γ-ray energy due to the greater absorption of lower energy γ rays in the plastic between the source and Ge(Li) detector. The work of Glascock, Talbert, and Duke[21] was used for the γ-ray intensities and for $N'_{\gamma g.s.}$. The I'_{β} value had an uncertainty of 2.9%. The ^{90}Rb β contamination correction was made separately for ^{90}Rb^{g} and ^{90}Rb^{m} with the level schemes and $\beta_{g.s.}$ values for ^{90}Rb^{g} and ^{90}Rb^{m} mentioned earlier used in making the contamination correction.

The first-excited state of ^{91}Sr at 93.6 keV has a half-life of 87 ± 3 nsec[21] and, hence, requires that Eq. (5) be used to correct for the double counts expected from this isomeric level. The total internal conversion coefficient for the 93.6-keV transition is 1.30 since the transition has been measured to be nearly pure $E2$.[23,24] Application of Eq. (5) gave the result that $I_{\beta c}$ is 71% of I'_{β}, hence, that 29% of the ^{91}Rb β counts are double counts from the 93.6-keV isomeric level. Application of Eq. (6) then gave the result $100 - \beta_{g.s.} = 102 \pm 8$, or $\beta_{g.s.} < 6$. This result is consistent with the $\beta_{g.s.}$ value of 5 ± 5 determined by Glascock, Talbert, and Duke[21] from relative γ-ray intensities for ^{91}Kr, ^{91}Rb, and ^{91}Sr. This latter value of 5 ± 5 is given in Table II since it is more accurate than the upper limit of 6 resulting from the 4π measurement. This $\beta_{g.s.}$ value is in serious disagreement with previous reports of 30 by Macias-Marques[25] and 60 ± 10 by Achterberg *et al.*[23] As discussed in Ref. 22, this discrepancy can only be attributed in part to differences in γ-ray intensities or the refinements in the decay scheme presented in Ref. 21. No complete explanation can be given for this discrepancy.

As was mentioned earlier, the ^{91}Rb data provide evidence that the threshold level of the β counter is below 80 keV. This evidence depends on the acceptance of the ^{91}Rb $\beta_{g.s.}$ value of 5 ± 5 and the low energy of the 93.6-keV isomeric level. If one assumed that the threshold level were above 93.6 keV, then none of the possible double-count events would occur and the $I_{\beta c}$ value would thus be equal to I'_{β}. With this assumption, the resulting value of $\beta_{g.s.}$ would be 27 ± 5. Assuming that all of the possible double-count events contribute to I'_{β} gives the upper limit $\beta_{g.s.}$ value of 6, as stated above, and corresponds to a threshold level low enough to allow all of the isomeric transitions to be detected. The actual situation is more likely to be somewhere between these two extremes. The $\beta_{g.s.}$ value of 5 can be used to provide an estimate of the threshold level energy. Our ^{91}Rb data would give a value of 5 for $\beta_{g.s.}$ if 18% of the maximum pos-

sible double-count events were below the threshold. This would imply that 22% of 78-keV K-conversion electrons occur below the threshold. Assuming a probable full width at half maximum of 15–20 keV for the response of the plastic scintillation detector of 78-keV electrons, the threshold level would be about 72 keV. The assumptions involved in this estimation, as well as the uncertainties in the various experimental quantities used, make this calculated threshold level speculative, but it is clearly quite plausible that the threshold level is below about 75 keV. In effect, then, the existence of an intense low energy isomeric level in ^{91}Rb provides a numerical value for the threshold level and verifies the less direct evidence from the ^{85}Kr^{m}, ^{87}Kr, and ^{138}Cs calibration sources that the threshold level is low enough to make β count losses negligible except in unusual cases like ^{91}Rb.

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[1]J. R. McConnell and W. L. Talbert, Jr., Nucl. Instrum. Methods 128, 227 (1975).

[2]F. K. Wohn, W. L. Talbert, Jr., and J. K. Halbig, Nucl. Phys. A152, 561 (1970).

[3]F. K. Wohn, J. K. Halbig, W. L. Talbert, Jr., and J. R. McConnell, Phys. Rev. C 7, 160 (1973).

[4]G. H. Carlson, W. L. Talbert, Jr., and J. R. McConnell, Phys. Rev. C 9, 283 (1974).

[5]J. H. Norman, W. L. Talbert, Jr., and D. M. Roberts, USAEC Report No. IS-1893, Iowa State University, 1968 (unpublished).

[6]M. J. Martin, Oak Ridge National Laboratory Report No. ORNL-4923, 1973 (unpublished).

[7]A. Shihab-Eldin, S. G. Prussin, F. M. Bernthal, and J. O. Rasmussen, Nucl. Phys. A160, 33 (1971).

[8]R. L. Bunting, W. L. Talbert, Jr., J. R. McConnell, and R. A. Meyer, Phys. Rev. C 13, 1577 (1976).

[9]R. C. Ragaini and J. D. Knight, Nucl. Phys. A125, 97 (1969).

[10]J. K. Halbig and F. K. Wohn (private communication).

[11]E. A. Henry, W. L. Talbert, Jr., and J. R. McConnell, Phys. Rev. C 7, 222 (1973).

[12]J. E. Kitching and M. W. Johns, Nucl. Phys. A98, 337 (1967).

[13]J. E. Kitching and M. W. Johns, Can. J. Phys. 44, 2661 (1966).

[14]J. R. Clifford, W. L. Talbert, Jr., F. K. Wohn, J. P. Adams, and J. R. McConnell, Phys. Rev. C 7, 2535 (1973).

[15]G. D. O'Kelley, N. H. Lazar, and E. Eichler, Phys. Rev. 102, 223 (1956).

[16]C. L. Duke and W. L. Talbert, Jr. (private communication).

[17]D. C. Kocher, Nucl. Data Sheets 16, 55 (1975).

[18]J. F. Mason and M. W. Johns, Can. J. Phys. 48, 2056 (1970).

[19]W. L. Talbert, Jr., C. L. Duke, and F. K. Wohn (private communication).

[20]N. R. Johnson, G. D. O'Kelley, and E. Eichler, Phys. Rev. 135, B36 (1964).

[21]M. D. Glascock, W. L. Talbert, Jr., and C. L. Duke, Phys. Rev. C 13, 1630 (1976).

[22]J. K. Halbig, F. K. Wohn, W. L. Talbert, Jr., J. J. Eitter, and J. R. McConnell, Nucl. Phys. A203, 532 (1973).

[23]E. Achterberg, F. C. Iglesias, A. E. Jech, J. A. Moragues, D. Otero, M. L. Perez, A. N. Proto, J. J. Rossi, and W. Scheuer, Phys. Rev. C 9, 299 (1974).

[24]F. K. Wohn, W. L. Talbert, Jr., R. S. Weinbeck, M. D. Glascock, and J. K. Halbig, Phys. Rev. C 11, 1455 (1975).

[25]M. I. Macias-Marques, Centre de Orsay, Universite Paris-Sud, Orsay Report Serie A, No. 843, 1971 (unpublished).