[6]$(N+O+\cdots\ )/M$ values were from O. Dragoun, Z. Plajner, and F. Schmutzler, Nucl. Data **A9**, 119 (1971).

[7]With the theoretical value (assumed exact) $\alpha_T = 0.1565$ for the 158.6 γ, we would obtain $\alpha_T(156.0\,\gamma) = 46.28 \pm 0.14$.

[8]J. C. Manthuruthil and J. H. Hamilton, in *Radioactivity in Nuclear Spectroscopy*, edited by J. H. Hamilton and J. C. Manthuruthil (Gordon and Breach, New York, 1972), p. 751.

[9]D. S. Brenner and M. L. Perlman, Nucl. Phys. **A181**, 207 (1972).

[10]H. C. Pauli, Computer Program for Internal Conversion Coefficients and Particle Parameters, The Niels Bohr Institute Report, 1968 (unpublished).

[11]F. Herman and S. Skillman, *Atomic Structure Calculations* (Prentice-Hall, Englewood Cliffs, N. J., 1963).

[12]C. C. Lu, T. A. Carlson, F. B. Malik, T. C. Tucker, and C. W. Nestor, Jr., Atomic Data **3**, 1 (1971).

[13]Hager and Seltzer employed a (2/3) value. The "correct" value probably lies between these extremes. See A. Rosén and I. Lindgren, Phys. Rev. **176**, 114 (1968).

[14]We briefly note here that the Sliv and Band values (based on the Thomas-Fermi-Dirac model) tend to be systematically $\approx 1\%$ lower than the Hager and Seltzer values. L. A. Sliv and I. M. Band, *Coefficients of Internal Conversion of Gamma Radiation* (Acad. Sci. USSR, Moscow-Leningrad), pt. 1 (1956), pt. 2 (1958).

PHYSICAL REVIEW C VOLUME 7, NUMBER 6 JUNE 1973

Decay Energies of Gaseous Fission Products and their Daughters for $A = 88$ to 93

J. R. Clifford,* W. L. Talbert, Jr., F. K. Wohn, J. P. Adams,† and J. R. McConnell

Ames Laboratory, U.S. Atomic Energy Commission and Department of Physics, Iowa State University, Ames, Iowa 50010

(Received 10 January 1973)

A systematic study of β-decay energies has been made for mass-separated activities of Kr gaseous fission products and their daughters at the TRISTAN on-line separator facility at the Ames Laboratory research reactor. A well-type plastic scintillator was used in coincidence with a Ge(Li) γ detector to determine β-group end-point energies and deduce Q values. The following β-decay energies have been determined: ^{88}Kr, 2.93 ± 0.03 MeV; ^{88}Rb, 5.30 ± 0.06 MeV; ^{89}Kr, 4.93 ± 0.06 MeV; ^{90}Kr, 4.35 ± 0.05 MeV; ^{90}Rb, 6.32 ± 0.07 MeV; ^{91}Kr, 6.12 ± 0.07 MeV; ^{91}Rb, 5.68 ± 0.04 MeV; ^{92}Kr, 5.97 ± 0.08 MeV; ^{92}Rb, 7.58 ± 0.15 MeV; ^{92}Sr, 1.93 ± 0.03 MeV; ^{93}Kr, 8.3 ± 0.5 MeV; and ^{93}Rb, 7.23 ± 0.10 MeV. The decay energies are compared with previous measurements, systematics predictions, and two currently accepted mass relations. The energies are used to predict the β-decay energies for 13 additional nuclei by means of systematics.

I. INTRODUCTION

In recent years the study of nuclear masses has been of interest for element-genesis theories in astrophysics and for predictions of decay properties of nuclei far from the line of β stability. This work is concerned with the latter interest and attempts to extend our knowledge of the changes in the nuclear mass surface, as determined from β-decay Q values, for several nuclei far from the line of β stability. The area of particular interest in this work is the neutron-rich region around the mass $A=90$.

The β-decay energies of short-lived nuclei have been predicted through mass relations that have parameters determined by using mass values for nuclei near the line of stability. Stimulated by an investigation of the astrophysical r process (rapid neutron-capture process), Seeger[1] modified the von Weizsacker liquid-drop model[2] by inclusion of shell-model effects and pairing terms, and created one of the more accurate models currently being used. Seeger used this mass formula to calculate the solar-system isotopic abundances of certain neutron-rich stable isotopes that resulted from the decay of extremely neutron-rich nuclides (20 to 40 units from the line of β stability) formed in conjectured astrophysical environments.

Another highly regarded approach to the prediction of decay energies is that developed by Garvey *et al.*[3] This mass relation is based on the single-particle model of the nucleus and utilizes symmetries implicit in isospin formalism. Relationships between nuclidic masses that are independent of the variation of mass with atomic number and charge are used to formulate a simple mass relation, which is then fitted to known data.

Though there are several other widely used mass formulas, those by Seeger and Garvey *et al.* are considered here to be the most acceptable since they have rather small deviations from experimentally determined masses. Furthermore, they are unique among the available formulas in their accuracy far from stability for neutron-rich nuclei since their predictions for the occurrence of delayed neutron precursors are in agreement with experimental observations.[4,5] These mass formulas have not, however, been subjected to a systematic test using mass differences experimentally determined for nuclei far from stability. This test is, in part, a justification for the work reported here.

An interesting systematic approach to the prediction of nuclear masses was taken by Way and Wood in 1954.[6] They developed a β-decay systematics which exhibits linear relations for disintegration energies between the nuclei (Z, N) and $(Z+1, N-1)$ when plotted as a function of N with Z constant, where Z is the proton number and N is the neutron number. These linear relations have been used to predict the mass differences for nuclei far from the line of β stability. Recently these predictions, as determined from presently available experimental results, were reported in the 1971 Atomic Mass Evaluation by Wapstra and Gove.[7] The measurement of masses far from stability in the present work should offer a specific test of these predictions and make possible several new predictions for nuclei even further away from the line of β stability. The new predictions may also lead the way towards improving present mass formulas or developing new relations that are applicable far from the line of stability.

Two types of experiments are reported in this work: β-decay Q-value measurements of singles β-ray spectra and end-point energies for β spectra in coincidence with γ rays. The experimental arrangement, described in detail by Clifford,[8] consists of a Ge(Li) γ-ray detector and a plastic-scintillator β-ray detector, whose response and calibration were determined. The spectra obtained were analyzed to obtain end-point energies and, in some cases, relative β branching to excited levels in the daughter nucleus.

II. EXPERIMENTAL ARRANGEMENT

The β-ray-spectrum measurements reported in this work were performed using the TRISTAN isotope separator on line to the Ames Laboratory research reactor.[9,10] With this facility, the ion beam of gaseous fission products from a mass separator is imbedded in an aluminized Mylar tape mounted inside a moving tape collector (MTC) which is used to provide isobaric separation between members of a decay chain with a given mass number. There are two detector ports in the MTC, shown in Fig. 1, that are 46 cm apart, as measured along the tape. The upper port, which is at the beam deposition point, is used for the study of parent and short-lived daughter activities, while the lower port is used for the study of the longer-lived daughter activities.

There are several modes of operation for the MTC. Depending on the half-life and the ancestry of the activity to be enhanced, the tape can be moved either continuously or intermittently in a stepping mode. Variation of such parameters as the tape speed, beam collection time, delay time, and count time determines the degree of enhancement of the activity of interest. The various modes of operation and the parameters involved are described in detail in a report by Norman, Talbert, and Roberts.[11]

The β-γ-coincidence detection system consists of a Ge(Li) γ-ray detector and a plastic-scintillator β-ray detector. The Ge(Li) detector is a 60-cm^3 coaxial-type detector having an 11% efficiency, a full width at half maximum resolution of approximately 2.8 keV and a peak-to-Compton ratio of 28:1 for the 1.33-MeV ^{60}Co transition. The plastic scintillator, shown in cross section in Fig. 1, is made of Pilot B plastic and has cylindrical symmetry with a diameter of 6.5 cm. The scintillator contains a well in the front face having the shape of a truncated cone with an entrance diameter of 1.9 cm and a depth of 2.3 cm. The plastic scintillator has a "depth" of 3.5 cm (the distance from the bottom of the well to the photomultiplier surface), equal to the range of a 7-MeV β ray in the Pilot B plastic. The well reduces the backscattering of β rays by an order of magnitude compared to a flat scintillator, but at the expense of some nonlinearity introduced into the calibration curve for low-energy β rays.

The plastic scintillator is mounted so that the source is positioned at the vertex of the cone, a distance of 5.7 cm from the front of the well. The detector is separated from the MTC by a wheel containing absorbers that are required for β-ray measurements described below, and a thin Mylar window to protect the detector from possible contamination. The absorber wheel has five aluminum and seven beryllium disks which range in thickness from 3.2 to 22.2 mm, as well as an "open" position.

The use of a scintillation detector for the study of continuous β-ray spectra requires a knowledge

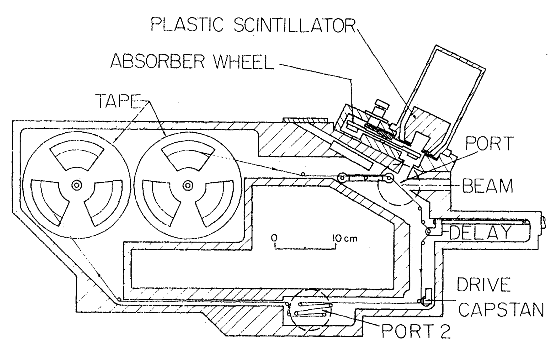

FIG. 1. Moving tape collector.

of the response of the scintillator to monoenergetic β rays. The determination of the response for the scintillation detector used in this work has been described in detail by Wohn *et al.*[12] The analysis of the measured spectra depends not only on the detail with which the β-ray response function is known but also on the accuracy of the energy calibration. The calibration technique is discussed in detail by Clifford[8] and Wohn *et al*. In all of the experimental runs involved in this work, sets of β-ray calibration spectra were taken both before and after each data run.

In the experiments described below, care was taken to control the source strengths to a level where summing effects in the β detector were not observable. It was found by analysis of singles β spectra of ^{137}Xe that count-rate-dependent distortions were not observed for count rates less than 3×10^4 counts/sec using 0.25-μsec bipolar shaping for the scintillator electronics channel. For the experiments described in this work, maximum singles count rates were typically 2×10^4 counts/sec. For this reason, we do not expect our results to contain any anomalous spectral effects due to summing.

III. DATA ACCUMULATION

The isotopes studied during this experiment were the short-lived gaseous fission products and their daughters for $A=88-93$. Knowing the half-lives of the members of each isobaric decay chain, values were obtained for the sample collect time, delay time, and data-accumulation time to give the desired activity enhancement. Table I lists the nuclei studied, and for each, the type of experiment (coincidence or singles), the MTC mode, and the integrated activity ratio as calculated from the program ISOBAR.[11] The MTC mode listed is either continuous, with the tape speed given in cm/sec or sequential, with the collect, delay, and accumulate times given in seconds.

For singles-β-spectrum measurements, a two-absorber method was used to obtain an approximate, unattenuated γ-ray spectrum which must be subtracted from the β-plus-γ spectrum collected without an absorber in order to deduce the distorted β-ray spectrum. An absorber just thick enough to stop the most energetic β-ray group and the next larger absorber were used during the scintillator calibration. The exponential absorption of γ rays through an absorber can be approximated by a straight line over a small-absorber thickness, with the result that the γ-ray spectrum for zero absorber thickness is given by

$$\gamma_0=\frac{t_2\gamma_1}{t_2-t_1}-\frac{t_1\gamma_2}{t_2-t_1},$$

where t_1 and t_2 are the absorber thicknesses, and γ_1 and γ_2 are the γ-ray spectra accumulated using these two absorbers. The two-absorber approximation gives 98.8% of the true, unattenuated γ-ray spectrum at 1 MeV, and 99.7% of the unattenuated γ-ray spectrum at 5 MeV, using the 0.625- and 0.750-cm Al absorbers, which stop a 5-MeV β ray. Since the measured β-ray spectra were usually fitted over the region between the end-point energy and an energy 2 MeV back from the end-point energy, the approximation appears to provide a valid correction for γ-ray contributions.

For coincidence β-spectrum measurements, a one-absorber method was used to obtain the γ-ray contribution which must be subtracted from the spectrum accumulated without an absorber in order to deduce the β-ray spectrum. During the experiment, data were taken with and without an absorber whose thickness was sufficient to stop the most energetic β-ray group. The data could be taken while the source activity varied as long as the MTC mode was unchanged, since the mode determined the activity ratios for the elements in the decay chain.

The number of γ-ray events accumulated for a specified live time could be considered independent of the absorber used, within the assumption that γ-ray absorption was negligible. Thus, in

TABLE I. Summary of experimental conditions.

Decaying nucleus	Coincidence of singles experiment	Moving-tape collector mode	Integrated activity ratios (%) Kr	Rb	Sr
^{88}Kr	Coin	Stationary tape	~47	~53	···
^{88}Rb	Coin	Stationary tape	~47	~53	···
^{89}Kr	Coin	0.10 [a]	99.5	0.5	···
^{89}Kr	Sing	0.77	100.0	···	···
^{90}Kr	Coin	40, 0, 40 [b]	84.0	16.0	···
^{90}Kr	Sing	1.02	99.8	0.2	···
^{90}Rb	Coin	60, 200, 190	3.0	97.0	···
^{90}Rb	Sing	60, 200, 190	3.0	97.0	···
^{91}Kr	Coin	0.43	98.3	1.7	···
^{91}Kr	Sing	0.77	99.0	1.0	···
^{91}Rb	Coin	30, 40, 60	5.0	95.0	···
^{92}Kr	Coin	0.41	82.0	18.0	···
^{92}Kr	Sing	4.42	97.8	2.2	···
^{92}Rb	Sing	10, 10, 10	4.0	96.0	···
^{92}Sr	Coin	1500, 1830, 1665	···	···	88
^{93}Kr	Coin	4, 0, 10	40.5	58.8	···
^{93}Kr	Sing	5.06	98.6	1.4	···
^{93}Rb	Coin	4, 0, 10	40.5	58.8	···
^{93}Rb	Sing	5, 2, 5	26.7	72.5	···

[a] Tape speed in cm/sec.
[b] Collect time, delay time, accumulate time in sec.

order to subtract out the γ-ray contribution from a γ-plus-β spectrum, a determination was necessary of the ratio of the time to accumulate a given number of events (e.g., 2048) with no absorber to that required to accumulate the same number of events with an absorber. During data accumulation, this time ratio was the proportionality constant between the number of coincidence events taken with an absorber and the number of events taken with no absorber.

This one-absorber technique assumes that there is little attenuation of the γ rays through the absorber. Though this assumption is not strictly true, the γ-ray attenuation is small, typically 5% over the region in which the measured spectrum is fitted. Moreover, the fact that the attenuation is energy-dependent partially compensates for the reduction in γ-ray counts at higher energies where the β-ray spectrum analysis is concentrated, since the number of high-energy γ rays compared to the number of low-energy γ rays accumulated in a given live time is enhanced by the absorber.

Approximately ten-million coincidence events were obtained and analyzed for each nucleus studied in this work. The β-ray spectrum gated by a γ-ray peak was adjusted to account for the Compton background contribution, thus giving the measured β-ray spectrum in coincidence with a given γ ray. The γ rays on which gates were placed were chosen to include both γ rays depopulating one level intensely fed by β decay, and γ rays depopulating all significantly fed levels. Singles measurements of β-ray spectra were taken for most nuclei to obtain a second determination of the β-decay energy and to identify any strong ground-state branching.

The analysis of the experimental data used a "folding" technique which involved first distorting the theoretical β-ray spectrum by folding in the response function, then least-squares fitting this distorted spectrum to the measured spectrum as described by Wohn *et al.*[12] and Clifford.[8] Whenever more than one β group was included in the least-squares fit, the relative intensities and end-point energies of the β groups were constrained to conform to the γ-ray decay scheme, thereby substantially reducing the number of fit parameters involved.

IV. RESULTS

The results of the analysis of the β-ray spectra for the 11 nuclei studied are presented below. A detailed summary exists for these results,[8] including a list of the gating γ rays, and the Q values deduced from the end-point energies of the coincident β-ray spectra with their uncertainties. The uncertainties in the Q values given here are a combination of the uncertainties in the least-squares fitting procedure and the uncertainties in the calibration function for the given energies.

Figures of spectra and fits are shown only to illustrate a point of contention with results expected from prior studies and in no way indicate the general quality of coincidence or singles spectra obtained for other gates and nuclei in this study. Unless specified in the text, reasonable fits to the data were obtained by analysis using constraints available from γ-ray decay schemes.

A. ^{88}Kr Decay

The Q value for the ^{88}Kr β decay is 2.93 ± 0.03 MeV, determined from β-ray spectra in coincidence with seven transitions depopulating three levels in ^{88}Rb. This value is in agreement with the value of 2.9 ± 0.1 MeV reported by Lycklama, Archer, and Kennett.[13] The decay scheme used in selecting the gating γ-ray transitions and in determining percent β branching to the various daughter energy levels was provided by Bunting.[14] The Q value reported here is a weighted average of the seven individually determined values.

B. ^{88}Rb Decay

For the ^{88}Rb decay, with the energy levels and γ-ray intensities again supplied by Bunting,[14] the β-ray spectra in coincidence with three γ-ray transitions have end-point energies giving a weighted-average Q value of 5.30 ± 0.06 MeV. This Q value is slightly higher than the 5.13 ± 0.08 MeV reported by Thulin[15] and the ^{88}Rb calibration energy of 5.17 ± 0.08 MeV, which is a weighted-average value determined from three previous measurements.[14-16] However, the measurement is in good agreement with the adjusted value of 5.30 ± 0.02 MeV determined by Wapstra and Gove[7] and with the recent magnetic-spectrometer measurement of 5.338 ± 0.004 MeV by Halbig and Wohn.[17]

C. ^{89}Kr Decay

In the decay of ^{89}Kr, the energy levels and the relative β branches to these levels were provided by Henry, Talbert, and McConnell.[18] The weighted average of Q values determined from seven gated β spectra is 4.93 ± 0.06 MeV.

One gate that has a rather interesting result is the 0.220-MeV gate. This work shows that there is no branching to the 0.220-MeV level and that the highest-energy β group for that gate populates the 0.477-MeV level. Kitching and Johns[19] report that a β group of end-point energy 4.90 ± 0.03 MeV populates the 0.220-MeV level, which would mean that the β-decay Q value would be 5.12 MeV. This result is 0.2 MeV higher than the Q value determined from the β-γ coincidence experiment. A more recent work from the same laboratory by Poehlman, Singh, and Johns[20] agrees with the more complete work of Henry, Talbert, and McConnell[18] in assigning zero β branching to the 0.220-MeV level on the basis of detailed γ-ray intensity balances.

D. ^{90}Kr Decay

The weighted average of the β-decay energies from eight γ-ray gates for the decay of ^{90}Kr is 4.35 ± 0.05 MeV. The singles β-ray spectrum Q value of 4.40 ± 0.06 MeV agrees with the average from the coincidence spectra, and with the former measurement of 4.41 ± 0.03 MeV by Mason and Johns.[21] The β-ray spectrum gated by the 1.423-MeV γ ray was fitted by a one-group theoretical spectrum which should reproduce the measured spectrum quite well, since there is no other branching to the 1.780-MeV level shown in the decay scheme of Mason and Johns. The spectrum appearance shown in Fig. 2, however, displays considerable low-energy intensity in the measured spectrum that is not accounted for by the one-group theoretical curve. This behavior, which is common to the four β-ray spectra gated by transitions from the 1.780-MeV level, indicates that there is significant β branching to a higher-energy level which depopulates through the 1.780-MeV level. It is difficult to reconcile this work with that of Mason and Johns, in which the 1.780-MeV level is reportedly fed only by a β transition, and which seems to be supported by preliminary results by Duke *et al.*[22] on the decay of ^{90}Kr. However, for the purposes of Q-value determination, the β spectra in coincidence with transitions depopulating the 1.780-MeV level gave end-point energies consistent with the Q value obtained

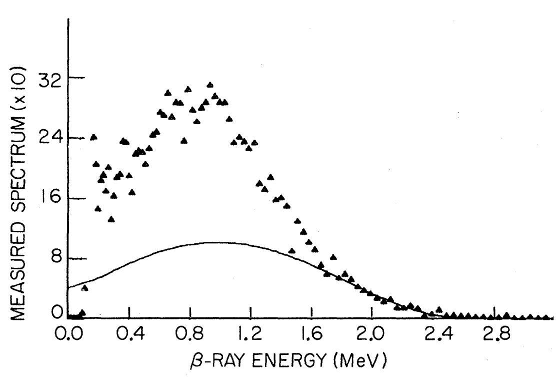

FIG. 2. β-ray spectrum in coincidence with the 1.423-MeV transition in the decay of ^{90}Kr, showing the fit obtained with direct β branching only to the level in ^{90}Rb at 1.780 MeV.

from other gated spectra for fits such as that in Fig. 2.

E. ^{90}Rb Decay

The ^{90}Rb β-decay energy was determined from three gated β-ray spectra to be 6.32 ± 0.07 MeV, while the singles measurement gives 6.34 ± 0.08 MeV. In 1964, Johnson, O' Kelley, and Eichler[23] measured the Q value to be 6.60 ± 0.09 MeV, which is 0.3 MeV higher than the present measurement. The agreement between the coincidence value determined using end-point energies having known calibration uncertainties and the singles value with an end-point energy beyond the calibration

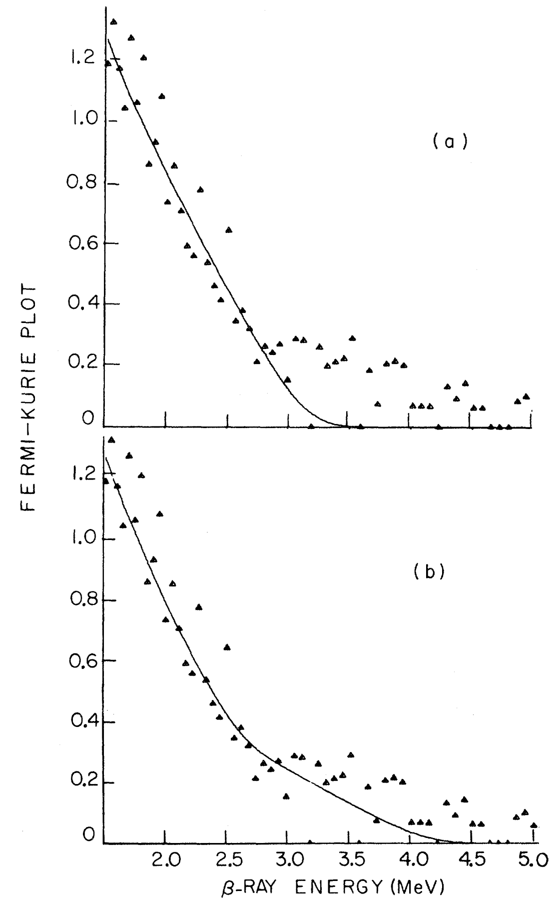

FIG. 3. (a) Fermi plot of the β-ray spectrum in coincidence with the 1.375-MeV transition in the decay of ^{90}Rb and the fit obtained using the β branching from Mason and Johns (Ref. 21). (b) Fermi plot of the β-ray spectrum in coincidence with the 1.375-MeV transition in the decay of ^{90}Rb and the fit obtained with the outer-β-group intensity reduced to approximately half that for the fit of Fig. 3(a), by means of reducing the β branching from the 0.106-MeV isomeric level in ^{90}Rb to about 2%.

limit indicates that the calibration is valid up to at least 6.3 MeV.

The β-ray spectrum gated by the 1.375-MeV γ ray was considered to be composed of β branching from the ground state of ^{90}Rb to the 3.450-MeV level in ^{90}Sr and from the isomeric 0.106-MeV level to four other contributing levels. Using the work of Johnson, O'Kelley and Eichler,[23] Mason and Johns[21] report that $16 \pm 3\%$ of the ^{90}Rb β transitions depopulate the 0.106-MeV isomeric state. Using the relative β intensities of Mason and Johns for the groups contributing to this gated spectrum, the Q value turns out to be too low by about 800 keV, compared to the results of the other gated spectra and the singles spectrum, and the fit to the 1375-keV gated spectrum is shown in Fig. 3(a). This fit has a residue at high energies because the intensity constraints from Mason and Johns make the outermost group too intense, moving the end-point energy of this group to a lower energy. If the decay scheme of Mason and Johns is rigorously followed, except for varying the ratio of ^{90}Rb ground-state to isomeric-state β decays, then the Q value resulting from this gated spectrum is consistent with that of the other spectra only by reducing the intensity of the outer β group by about half, resulting in the fit shown in Fig. 3(b). This manipulation of component group intensities requires that only about 2% of the β transitions in the decay of ^{90}Rb originate from the isomeric level, which is very difficult to reconcile to the gross γ-ray results of both Mason and Johns and Duke *et al.*[22]

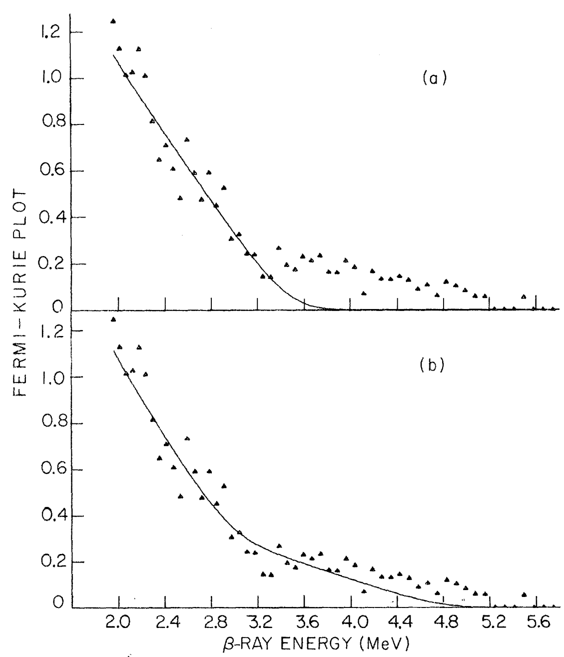

FIG. 4. (a) Fermi plot of the β-ray spectrum in coincidence with the 0.603-MeV transition in the decay of ^{91}Rb and the fit obtained with 5.8% β branching to the 1.041-MeV level of ^{91}Sr. (b) Fermi plot of the β-ray spectrum in coincidence with the 0.603-MeV transition in the decay of ^{91}Rb and the fit obtained with 0.6% β branching to the 1.041-MeV level of ^{91}Sr.

The γ-γ coincidence studies of Duke *et al.* preliminarily indicate that the 1375-keV transition intensity is split incorrectly in its double placement in the decay scheme of Mason and Johns. The outer β-group intensity for the spectrum in coincidence with this transition is very sensitive to adjustments in the intensity split, and in fact is lowered enough to provide a fit similar to that in Fig. 3(b) by adjusting the intensity split, as indicated from Duke *et al.*, to decrease the 1375-keV (2206- keV to 832-keV) transition intensity by only 7%. This small adjustment also results in a Q value consistent with the other determinations.

Mason and Johns also report that there is a 1.119-MeV transition in ^{90}Sr, which is likewise seen in ^{90}Rb. The Q value determined from the β-ray spectrum in coincidence with this 1.119-MeV γ ray verifies the work of Duke *et al.*,[22] which explains the reported double presence of this transition[20] as due to ^{90}Kr activity contaminating the ^{90}Rb decay data, and which favors the assignment of this γ ray to the ^{90}Kr decay alone.

F. ^{91}Kr Decay

Using the preliminary decay scheme of Duke *et al.*,[22] the β branches to levels in ^{91}Rb were calculated. The β-decay Q value averaged from the analysis of four gated spectra is 6.12 ± 0.07 MeV. The β singles end-point energy measurement of 6.25 ± 0.08 MeV is within the uncertainty of the β-γ average decay energy. In 1970, Eidens, Roeckl, and Armbruster[24] reported the Q value to be 5.7 ± 0.4 MeV, which is not consistent with these other values nor with the predictions of the Way-Wood diagrams.[7]

G. ^{91}Rb Decay

The Q value for the decay of ^{91}Rb was determined, using six coincidence β-ray spectra, to be 5.68 ± 0.04 MeV. This is in excellent agreement with the work in 1968 by Zherebin *et al.*,[25] who reported a value of 5.68 ± 0.15 MeV. Mason and Johns[26] developed a level scheme with the 1.041-MeV level populated by 5.8% of the β transitions from ^{91}Rb. The β-ray spectrum coincident with the 0.603-MeV γ ray depopulating this level is shown in Fig. 4(a). The present work indicates that the value of 5.8% branching to the 1.041-MeV level is much too large, since a better fit to the spectrum, as shown in Fig. 4(b), is obtained with a branching of about 0.6% (which is also necessary to obtain a consistent value for Q_β with this gate). Furthermore, a better fit to the 0.439-MeV gated β-ray spectrum with lower branching to the 1.041-MeV level is an additional indication that the percent β branching to this level, as assigned by Mason and Johns, is too high. A more accurate value for the branching intensity to the 1.041-MeV level awaits the completion of analysis of data taken by Duke *et al.*,[22] which preliminarily raises serious questions about the validity of the decay scheme of Mason and Johns.[26]

H. ^{92}Kr Decay

The previously unmeasured β-decay Q value for the ^{92}Kr decay was determined using both coincidence β-ray spectra and a singles β-ray spectrum. The eight gated spectra give an average Q value of 5.97 ± 0.08 MeV and the singles-spectrum end-point energy was 5.95 ± 0.08 MeV. Though there are no other values with which to compare these results, the agreement between the coincidence and singles values is evidence for the accuracy of the measurements, and of the previously determined γ-ray decay scheme. The energy levels and the percent β branching for the decay of ^{92}Kr were taken from the study of Olson, Talbert, and McConnell.[27] One discrepancy was found between this work and that of Olson, Talbert, and McConnell regarding the reported percent β branching to the ground state of ^{92}Rb. Using the ground-state branching of 50% assigned by Olson, Talbert, and McConnell, the calculated β-ray spectrum, shown in Fig. 5(a) is a much poorer fit to the measured singles spectrum than that obtained using a ground-state β branching on the order of 2%, which results in the β-ray spectrum fit shown in Fig. 5(b). In addition, the lower β branching to the ground state gives rise to a more reasonable log *ft* value for the expected first-forbidden ground-state β-ray transition.[27] Included in the analyses of the singles spectra was significant contamination from the decay of ^{92}Rb, which has an end-point energy of 7.5 MeV.

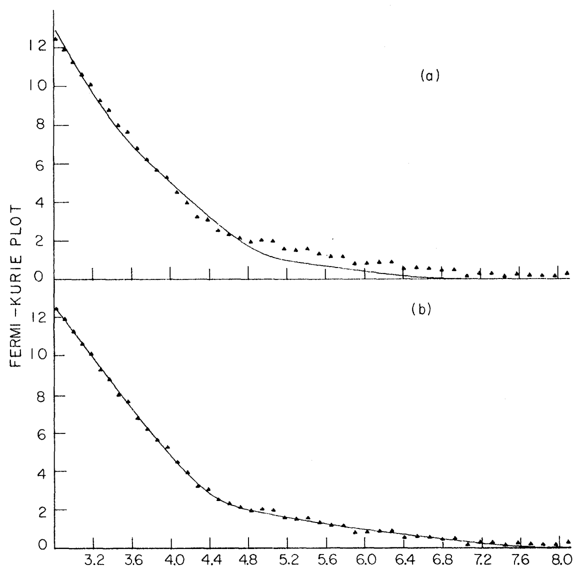

FIG. 5. (a) Fermi plot of the β singles spectrum for the decay of ^{92}Kr and the fit obtained with 50% β branching to the ground state of ^{92}Rb. (b) Fermi plot of the β singles spectrum for the decay of ^{92}Kr and the fit obtained with 2% β branching to the ground state of ^{92}Rb.

I. ^{92}Rb Decay

For the decay of ^{92}Rb, a β singles measurement only was made, giving a β-decay end-point energy of 7.58 ± 0.15 MeV. The high uncertainty in the measured value is due to the fact that the calibration function is not well known above the fit region, 4.0 to 6.4 MeV. The comparison between coincidence and singles measurements for ^{90}Rb and ^{91}Kr is evidence, however, that the calibration function is linear from 3.0 to 6.3 MeV. The spectrum intensity above 7 MeV could be slightly too low due to incomplete absorption of electron energies, but the addition of these counts to the lower-energy portion of the spectrum should be negligible in comparison to the counts expected below 7 MeV. Figure 6 shows the Fermi plot of the fit with two β groups, one a 94% ground-state branch and the other a 1.3% branch to the 0.815-MeV state, as determined by Olson, Talbert, and McConnell.[27] The β-decay Q value reported here does not agree with the 8.18 ± 0.13 MeV reported by Macias-Marques *et al.*,[28] who claim that a β group having an end-point energy of 7.4 MeV populates the

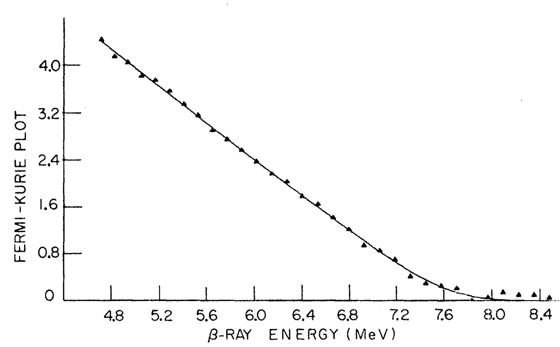

FIG. 6. Fermi plot of the β singles spectrum for the decay of ^{92}Rb.

TABLE II. Values of β-decay energies for ^{93}Kr and ^{93}Rb.

Gating transition (MeV)	β-decay end-point energy (MeV)	Isobaric identification of gating transition
0.182	7.02 ± 0.10	Kr
0.253	7.23 ± 0.10	Kr
0.267	7.02 ± 0.10	Kr
0.323	7.12 ± 0.10	Kr
0.431	5.32 ± 0.11	Rb

0.815-MeV level. If Macias-Marques *et al.* were correct, then a prominent higher-energy group should have been seen in the singles spectrum, since the work of Olson, Talbert, and McConnell showed that the upper limit to the β branching to the 0.815-MeV level is 25%, compared to the ground-state β branching. This group was not seen in the present work.

J. ^{92}Sr Decay

The Q value for the decay of ^{92}Sr was determined to be 1.93 ± 0.03 MeV, from analysis of the β-ray spectrum obtained in coincidence with the 1.384-MeV transition in ^{92}Y. This value agrees with the value 1.92 ± 0.07 MeV adopted by Wapstra and Gove.[7] There were no other significant β-ray spectra in coincidence with other, weaker γ rays in the decay of ^{92}Sr, as expected from the work of Olson, Talbert, and McConnell.[27] No β singles measurement was made for this decay.

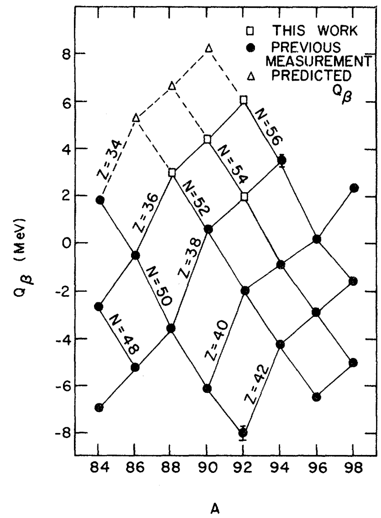

FIG. 7. Way-Wood diagram for even-A–even-Z nuclei in the mass region around $A = 90$.

K. ^{93}Kr and ^{93}Rb Decays

The decay schemes for ^{93}Rb and ^{93}Sr have not been determined, hence no Q value can be determined using β-γ-coincidence-spectra end-point energies. The gated β-ray spectra, however, do provide a lower limit to the β-decay end-point energy. The four end-point energies determined from gating transitions in the ^{93}Kr decay listed in Table II are around 7.1 MeV. The similarity of all the end-point energies for the gated specta suggest that the transitions chosen depopulate or follow depopulation of a single level that is heavily fed by β decay. A singles spectrum was also

TABLE III. β-decay energy results.

	Predicted energy			Experimental results, this work		
Decaying nucleus	Garvey *et al.* (Ref. 3) (MeV)	Seeger (Ref. 1) (MeV)	Wapstra and Gove (Ref. 7) (MeV)	Coincidence determination (MeV)	No. gates used	Singles determination (MeV)
^{88}Kr	2.81	2.1	2.90 ± 0.10	2.93 ± 0.03	7	···
^{88}Rb	5.07	5.2	5.30 ± 0.02	5.30 ± 0.06	4	···
^{89}Kr	5.11	5.1	5.15 ± 0.03	4.93 ± 0.06	7	4.84 ± 0.16
^{90}Kr	4.18	3.7	4.41 ± 0.03	4.35 ± 0.05	8	4.40 ± 0.06
^{90}Rb	6.41	6.4	6.63 ± 0.09	6.32 ± 0.07	3	6.34 ± 0.08
^{91}Kr	6.46	6.8	6.5 [a]	6.12 ± 0.07	4	6.25 ± 0.08
^{91}Rb	5.49	5.0	5.68 ± 0.15	5.68 ± 0.04	6	···
^{92}Kr	5.31	5.1	···	5.97 ± 0.08	8	5.95 ± 0.08
^{92}Rb	7.78	8.0	7.9 [a]	···		7.58 ± 0.15
^{92}Sr	1.82	1.0	1.92 ± 0.07	1.93 ± 0.03	1	···
^{93}Kr	8.15	8.6	···	···		8.30 ± 0.50
^{93}Rb	6.62	6.4	6.9 [a]	···		7.23 ± 0.10

[a] Predicted by systematics.

taken but the lever arm for the highest-energy group is not long enough to give an accurate measurement of the Q value. The outer-group end-point energy from singles-spectrum analysis is 8.3 ± 0.5 MeV. There is also some evidence in the singles spectrum of a strong β group with an end-point energy of 6.2 ± 0.1 MeV. The singles spectrum, however, does not appear to contain a β group with the end-point energy of 7.1 MeV that seems to be prevalent for the gated spectra.

The single gated β-ray spectrum for the decay of ^{93}Rb, which is also listed in Table II, has an end-point energy of 5.32 ± 0.11 MeV. The β singles spectrum gives a good measurement of the β-decay Q value, 7.23 ± 0.10 MeV, assuming the outer β group is a ground-state transition. When the decay schemes have been determined, the β-γ-coincidence-spectra end-point energies presented here should provide better Q-value determinations, as well as prove useful in the construction of the decay schemes.

V. DISCUSSION

A summary of the results of this work is given in Table III, which lists the average Q values from the gated coincidence β-ray spectra with the associated uncertainties, the number of gates used in determining the average values, and the Q values resulting from the analysis of the singles β-ray spectra. Also included in the table are the Q values predicted by the Seeger[1] and Garvey *et al.*[3] formalisms as well as the experimental results and systematic predictions reported in the compilation by Wapstra and Gove.[7] The predicted energies according to Garvey *et al.* are essentially as close to those measured in this work as are those of Seeger. The weighted rms deviation for the Garvey mass relation is 0.22 MeV, while that for the Seeger mass formula is 0.20 MeV. Garvey *et al.* quote an rms deviation of 0.20 MeV for their fit to all the known masses, which is slightly less than the rms deviation of their predictions for the β-decay energies measured in this work. Seeger quotes an rms deviation of 0.73 MeV to the known masses, which is considerably more than the rms deviation of his predictions for the Q values measured in this work.

A correction to the Garvey *et al.* mass formula was developed by Sorensen[29] to account for the long-range, liquid-drop features of the nuclear masses. The corrected mass calculations were compared to the experimental results presented in this work and found to give no lower rms deviation than for the uncorrected values. Also, no apparent trend or pattern was established toward decreasing average deviations using the Sorensen calculations. It appears that the mass relation of Garvey *et al.* could be used to advantage to predict β-decay energies for short-lived radioactive nuclei likely to be studied in the reasonable future, on the basis of its small deviation from all known masses. The mass formula of Seeger, however, is perhaps uncontested, although untested directly, for use in the extreme neutron-rich region traversed in nucleogenesis calculations.

The systematic approach to determining β-decay energies established by Way and Wood[6] is a "bootstrapping" technique which can be used for predicting unknown β-decay energies from the β-decay energies of the adjacent nuclei. The Way-Wood

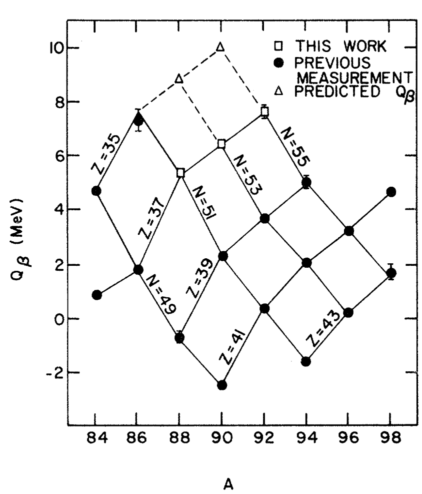

FIG. 8. Way-Wood diagram for even-A–odd-Z nuclei in the mass region around $A = 90$.

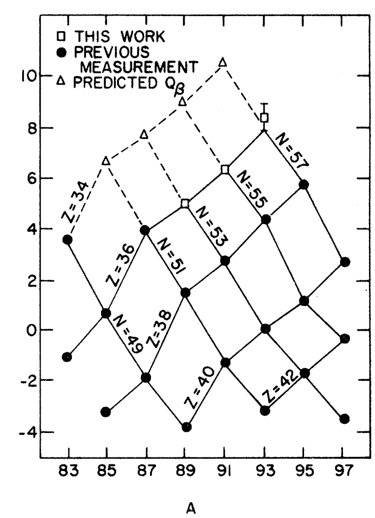

FIG. 9. Way-Wood diagram for odd-A–even-Z nuclei in the mass region around $A = 90$.

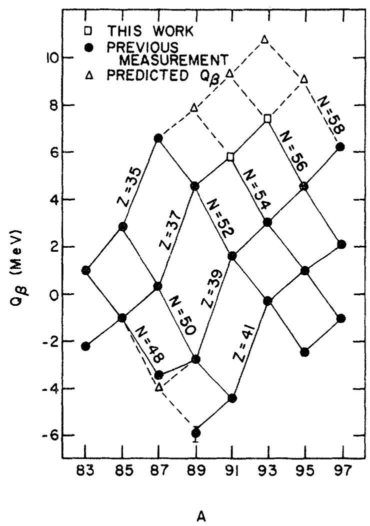

FIG. 10. Way-Wood diagram for odd-A–odd-Z nuclei in the mass region around $A = 90$.

TABLE IV. Predicted β-decay energies.

Decaying nucleus	Systematic predictions (MeV)	Garvey *et al.* (Ref. 3) (MeV)	Seeger (Ref. 1) (MeV)
^{85}Se	6.8	5.9	6.3
^{86}Se	5.3	5.0	4.5
^{87}Se	7.9	7.3	7.5
^{88}Se	6.7	6.3	6.2
^{89}Se	9.2	8.6	9.2
^{90}Se	8.4	7.5	7.2
^{91}Se	10.8	10.3	10.9
^{88}Br	8.7	9.0	8.4
^{89}Br	7.7	8.0	7.0
^{90}Br	9.9	10.3	10.1
^{91}Br	9.3	9.2	8.3
^{93}Br	11.0	10.4	10.0
^{95}Rb	8.9	7.9	7.9

diagrams for even-A–even-Z, even-A–odd-Z, odd-A–even-Z, and odd-A–odd-Z which illustrate the two approximately linear relationships for the decay energies of the masses studied in this work are shown in Figs. 7 – 10. The filled circles mark the previously measured β-decay Q values, the open squares mark the Q values measured in this study, and the open triangles mark the β-decay energies predicted on the basis of the parallelogram structure. The lines of constant Z and N are labeled and dashed lines connect the predicted Q values with the measured ones. At the major shell closure for $N = 50$ a significant discontinuity in the slope of the constant-Z lines is apparent, but the slope change appears independent of Z for neighboring lines. The weighted rms deviation of the Way-Wood systematics predictions for the nuclei studied in this work is 0.46 MeV.

Extending these systematics by using the new values reported here, 13 new β-decay end-point energies were predicted and are listed in Table IV, along with the calculations of Garvey *et al.* and Seeger. The Way-Wood technique of predicting the Q values is probably no more accurate than 0.5 MeV when extrapolating from experimentally determined values. The errors compound when the predictions are partially based on other systematically determined values. A comparison between the systematic predictions and the Garvey *et al.* or Seeger calculations shows discrepancies which are larger than those cited for the mass relations. Which, if any, of these is accurate will have to be determined by future experiments. Where systematic predictions of the type developed by Way and Wood are based on accurate values, these seem to give reasonable accuracy and may indicate where experimental measurements need to be improved.

*Present address: Physics Department, U.S. Air Force Academy, Colorado 80840.

†Present address: Physics Department, University of Notre Dame, Notre Dame, Indiana 46556.

[1]P. A. Seeger, CERN Report No. 70-30, 1970 (unpublished), Vol. 1, p. 217.

[2]C. F. von Weizsäcker, Z. Phys. **96**, 431 (1935).

[3]G. T. Garvey, I. Kelson, W. J. Gerace, R. L. Jaffe, and I. Talmi, Rev. Mod. Phys. Suppl. **41**, S1 (1969).

[4]W. L. Talbert, Jr., A. B. Tucker, and G. M. Day, Phys. Rev. **177**, 1805 (1969).

[5]W. L. Talbert, Jr., Phys. Rev. C **1**, 1135 (1970).

[6]K. Way and M. Wood, Phys. Rev. **94**, 119 (1954).

[7]A. H. Wapstra and N. B. Gove, Nucl. Data A **9**, 265 (1971).

[8]J. R. Clifford, Ph.D. thesis, Iowa State University, 1972 (unpublished).

[9]W. L. Talbert, Jr., and D. Thomas, Nucl. Instrum. Methods **38**, 306 (1965).

[10]W. L. Talbert, Jr., and J. R. McConnell, Ark. Fys. **36**, 99 (1967).

[11]J. H. Norman, W. L. Talbert, Jr., and D. M. Roberts, U.S. Atomic Energy Commission Report No. IS-1893, Iowa State University, 1968 (unpublished).

[12]F. K. Wohn, J. R. Clifford, G. H. Carlson, and W. L. Talbert, Jr., Nucl. Instrum. Methods **101**, 343 (1972).

[13]H. Lycklama, N. P. Archer, and T. J. Kennett, Can. J. Phys. **47**, 493 (1969).

[14]R. L. Bunting, Ph.D. thesis, Iowa State University, 1972 (unpublished).

[15]S. Thulin, Ark. Fys. **9**, 137 (1955).
[16]M. E. Bunker, L. M. Langer, and R. D. Moffat, Phys. Rev. **81**, 30 (1972).
[17]J. K. Halbig and F. K. Wohn, private communication.
[18]E. A. Henry, W. L. Talbert, Jr., and J. R. McConnell, Phys. Rev. C **7**, 222 (1973).
[19]J. E. Kitching and M. W. Johns, Nucl. Phys. **A98**, 337 (1967).
[20]W. F. S. Poehlman, B. Singh, and M. W. Johns, Can. J. Phys. **50**, 2741 (1972).
[21]J. F. Mason and M. W. Johns, Can. J. Phys. **48**, 2056 (1970).
[22]C. L. Duke, B. R. Erdal, K. O. Nielsen, R. J. Olson, and W. L. Talbert, Jr., private communication with C. L. Duke.
[23]N. R. Johnson, G. D. O'Kelley, and E. Eichler, Phys. Rev. **135**, B36 (1964).
[24]J. Eidens, E. Roeckl, and P. Armbruster, Nucl. Phys. **A141**, 289 (1970).
[25]E. A. Zherebin, A. I. Krylov, V. J. Polikarpov, and M. N. Yuzyuk, Yad. Fiz. 7, 3 (1968)]. [Sov. J. Nucl. Phys. 7, 1 (1968)].
[26]J. F. Mason and M. W. Johns, Can. J. Phys. **48**, 2895 (1970).
[27]R. J. Olson, W. L. Talbert, Jr., and J. R. McConnell, Phys. Rev. C **5**, 205 (1972).
[28]M. I. Macias-Marques, R. Foucher, M. Caillian, and J. Belhassen, CERN Report No. 70-30, 1970 (unpublished), Vol. 1, p. 321.
[29]R. A. Sorensen, Phys. Lett. **34B**, 21 (1971).

PHYSICAL REVIEW C VOLUME 7, NUMBER 6 JUNE 1973

Nuclear Spectroscopy Studies on the Alpha Decay of ^{235}Np and Beta Decay of ^{231}Th †

E. Browne and F. Asaro
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
(Received 12 January 1973)

The α decay of ^{235}Np has been studied by quantitative α singles and α-γ coincidence techniques, and the β decay of ^{231}Th by quantitative γ-ray singles and γ-γ two-parameter coincidence measurements with semiconductor detectors. Rotational bandheads in ^{231}Pa at 102.30, 174.10, and 183.47 keV are given the Nilsson assignments $[\Omega\pi(N n_z \Lambda)] \frac{3}{2}+(651)$, $\frac{5}{2}-(523)$, and $\frac{5}{2}+(642)$. Decay schemes for ^{235}Np and ^{231}Th are presented as well as a transition intensity balance for ^{231}Th which includes β branchings. Energy level spacings and α, β, and γ transition probabilities are interpreted in terms of a strong Coriolis interaction among the even-parity rotational bands and admixtures in the wave functions are given for the observed levels.

I. INTRODUCTION

The low-lying energy levels of ^{231}Pa and ^{233}Pa are of particular interest because of the strong Coriolis forces between a number of states, and the opportunity to see the effect of these forces not only on the energy level spacings but also on the α, β, and γ transition probabilities.

This study on ^{231}Pa energy levels was prompted by an earlier investigation of ^{237}Np α decay[1] which demonstrated distortions in the energy level spacings and in the α and γ transition probabilities. Concurrent with the present study, Hoekstra and Wapstra,[2] in their paper on the energy levels of ^{233}Pa, also suggested ^{231}Pa might be similar. The study of ^{235}Np α decay is complicated by the minute α branching of this predominately electron-capture activity.

In the present work, which has been reported in preliminary fashion earlier,[3-5] quantitative α-γ coincidence measurements were made on ^{235}Np and quantitative γ-ray singles and γ-γ coincidence measurements on ^{231}Th. Four new energy levels are observed and two more are assigned different energies. Reassignments of Nilsson quantum numbers are made for the states at 84.17 and 183.47 keV and a new assignment is made for the rotational band head at 174.10 keV. An intensity balance is performed for both β and γ transitions in ^{231}Th decay.

The even-parity energy levels in ^{231}Pa are interpreted with a complete Coriolis calculation and admixtures in the wave functions are obtained for each observed state. Although the experimental ratios of the α, β, and γ transition probabilities to the even-parity states are rather unusual, they agree reasonably well with calculated results if Coriolis-mixed wave functions are used.

II. SOURCE PREPARATIONS

^{235}Np was produced by bombarding 1 g of highly enriched (94.4%) ^{235}U with 18-MeV deuterons for 978-μAh in the 88-in. cyclotron at the Lawrence Berkeley Laboratory. The uranium target was dissolved in 10 M HCl and adsorbed onto a Dowex AG1-X8 anion exchange column. Washes with more 10 M HCl removed the fission products, and elution of the column with 2.7 M HCl removed the