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STUDY OF ELECTRON EMISSIONS OF SOME MASS
SEPARATED FISSION PRODUCT ACTIVITIES

Ph.D. Thesis Submitted to Iowa State University,
August, 1972

MASTER

J. P. Adams

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Study of electron emissions of some
mass separated fission product activities

by

James Paul Adams

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V

Study of electron emissions of some
mass separated fission product activities

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The beta decay energies for seven short-lived radioactive nuclei produced at the TRISTAN experimental facility were measured using a plastic scintillator and a Ge(Li) detector in a beta-gamma arrangement. The beta decay energies were compared with previous measurements and systematics predictions and were used to predict the beta decay energies for 5 additional nuclei by means of systematics. The beta decay energies were also compared with 2 currently accepted mass formulas. In addition, an internal conversion electron measurement was made for the decay of 16-sec ^{140}Xe . Probable multipolarities for 18 gamma transitions in ^{140}Cs were determined and, on the basis of these multipolarities and the calculated log ft values for the beta fed levels in the decay scheme of ^{140}Cs , the spins and parities for 15 levels in this decay scheme are proposed.

1. INTRODUCTION

As a result of nuclear fission, neutron-rich nuclei are formed. Most of these nuclei are radioactive, that is, they are unstable toward emission of an electron and anti-neutrino and thus beta decay with half-lives ranging from milliseconds to years. The maximum energy of the beta spectrum is equal to the difference in the masses of the decaying or "parent" nucleus and the subsequent or "daughter" nucleus. Since the mass of a nucleus is the sum of the rest masses of the individual nucleons minus the binding energy holding the nucleus together, knowledge of the mass of a nucleus gives information about the effects of the nuclear forces acting between nucleons. For example, the mass differences between adjacent isotopes (isotones) reflect the binding energies of the last neutron (proton) in nuclei (1). Knowledge of the ground state feeding and beta decay end-point energy is necessary for an unambiguous determination of the comparative half-life, or $\log ft$ value of a particular beta group, which can be used to predict a range for the spin-parity difference between the energy levels connected by the beta group.

In this work, the beta decay end-point energies of seven decaying nuclei were measured, using beta-gamma coincidence and beta singles techniques: the nuclei studied were ^{140}Xe , ^{140}Cs , ^{141}Xe , ^{141}Cs , ^{141}Ba , ^{142}Xe , and ^{142}Cs . As an unstable nucleus beta decays, the resulting or "daughter" nucleus is often formed in an excited state, and will de-excite emitting a photon. The end-point energy of the beta group feeding an energy level in the "daughter" nucleus is equal to the beta decay energy of the "parent" nucleus minus the excitation energy of the "daughter"

nucleus. Since the gamma ray de-exciting the "daughter" nucleus is in time coincidence with the beta particle emitted from the "parent" nucleus, the beta decay energy of the "parent" nucleus can be determined by measuring the end-point energy of the beta group in coincidence with the de-exciting gamma ray. Of the nuclei studied in this work, the 1971 compilation by Wapstra and Gove (2), includes five nuclei, ^{140}Xe , ^{141}Xe , ^{141}Cs , ^{142}Xe , and ^{142}Cs , which had been only predicted previously. Alväger et al. estimated the beta end-point energies for ^{140}Cs , ^{140}Xe , and ^{142}Cs to be 6.2 ± 0.6 MeV, 4.7 ± 0.5 MeV, and 7.6 ± 0.8 MeV, respectively (3). However, Wapstra and Gove did not incorporate these estimates into their compilation. Zharebin et al. measured the beta decay energy for ^{140}Cs to be 5.7 ± 0.1 MeV (4). In 1948, Levy and Zemal reported the beta decay energy for the decay of 18-min ^{141}Ba to be 2.9 MeV (5). Maly et al., in 1958, measured the energy of the same decay to be 1.93 MeV (6). The most recently reported measurement for this energy was by Fritze and Kennett who, in 1962, determined it to be 3.0 ± 0.1 MeV (7). This latest value for the decay energy was reported in the compilation by Wapstra and Gove. The discrepancies in the reported measurements of this particular beta decay energy present a need to remeasure this energy in order to resolve this issue.

In addition, the decay energies of ^{140}Xe , ^{141}Cs , and ^{142}Cs were predicted to be 4.3, 5.1, and 6.7 MeV by Wapstra and Gove (2). In this prediction, they required simultaneous smoothness of two-neutron separation energies, two-proton separation energies, alpha-decay energies and beta-decay energies for their estimation, using the method developed by Way

and Wood (2,8). This method makes use of the prediction (derived from the semi-empirical mass formula of Von Weisaecker) that the beta decay energy varies approximately linearly with N , the neutron number, if either A , $I (=N - Z)$ or Z is held constant (8). This linear dependence is illustrated in Figure 1 for the mass region around $A = 108$, where the values for the beta decay energies have been taken from the compilation of Wapstra and Gove. The deviation from linearity is most pronounced in mass regions near either shell closure or nuclear deformation.

The beta decay energies measured in this work were compared with two mass formulas or laws: 1) the liquid drop model semi-empirical mass law developed by Von Weisaecker and expanded to include shell effects and BCS theory pairing energies by P. Seeger (9); and 2) the isospin-based mass relation developed by Garvey et al. (10). All mass formulas are semi-empirical in nature, that is, the values for the parameters that make up the formulas are determined using experimental results. Since the majority of the available data come from the "near-stable" nuclei, the mass formulas are most accurate in this region. These mass formulas are often used to predict properties of nuclei in regions not accessible by experiment and sometimes far removed from stability. An example of this is reported by P. Seeger (9) in his discussion of the "r-process" of nucleogenesis. Knowledge of the masses in the extreme "neutron-rich" region far from the line of beta stability is desired to extract the conditions (temperature, neutron flux, etc.) that are necessary to sustain the "r-process." Seeger uses several mass formulas to predict the relative isotopic abundances resulting from this process. Of all the formulas he

Figure 1. Way-Wood diagram for even-even nuclei around $A=108$

tested, his own came closest to predicting the naturally occurring isotopic abundances.

Another example of the extrapolation of the mass formulas is in the area of "super-heavy" elements, a subject of great contemporary interest. J. R. Nix has proposed a means of predicting fission barriers for the (as yet) undiscovered super-heavy nuclei by synthesizing a microscopic theory, the shell model, with the macroscopic liquid-drop model (11). He reasons that the liquid-drop model should predict the smoothly varying trends of the nuclear potential and the shell model should predict the local fluctuations such as shell closure. In doing this, he relies on a mass formula based on the liquid-drop model presumed to work well for heavy nuclei (12).

In these varied predictions, the mass formulas use known data near stability to predict information either far from stability or near stability for the super-heavy nuclei. Measurement of masses far from stability offers, perhaps, the most critical test of these extrapolations, and may indicate ways to improve the mass formulas. Another example of the use of these mass formulas is in the prediction of delayed neutron precursors. An excited nucleus can de-excite via emission of a neutron if the beta decay energy of its "parent" or precursor is larger than the binding energy of its least tightly bound neutron. Therefore, a mass formula can be tested in its ability to predict the occurrence of delayed neutron precursors. The formulas developed by Seeger (9) and Garvey et al. (10) were chosen for comparison with the results of this work from the other available mass formulas because of their ability to predict the

occurrence of delayed neutron precursors, (13,14) as well as their relative accuracy in fitting known masses.

In addition to the measurement of beta decay energies, the internal conversion coefficients of several gamma rays associated with the beta decay of ^{140}Xe were measured in this work. These coefficients were then compared with the theoretical predictions compiled by Hager and Seltzer (15) to deduce possible transition multipolarities. For a description of the theory of the internal conversion process, the reader is referred to a review article by Rose in Alpha-, Beta- and Gamma-Ray Spectroscopy (ed. Siegbahn) (16). The tabulated coefficients by Hager and Seltzer are used because they represent the most recent and complete calculations of internal conversion coefficients (17). In these calculations, corrections are made for the "static" effect of the finite nuclear size by the use of a realistic nuclear charge density with a Fermi shape. The tables include the coefficients for all the K, L and M subshells for $30 \leq Z \leq 103$ within a wide range of gamma transition energies. In the case of Cs, ($Z = 55$), the K-, L-, and M-subshell conversion coefficients are tabulated for transition energies ranging from the threshold energies up to 1.55 MeV, 1.5 MeV and .5 MeV, respectively, and for $E\ell$ and $M\ell$ multipolarities from $\ell = 1$ to 4. Since the coefficients were calculated for only a finite number of transition energies, a Fortran computer program ICCS, furnished as a part of the compilation, is used to find values of conversion coefficients for actual transition energies by numerical interpolation, based on spline interpolation (cubic) and providing a piecewise polynomial fit to the data (18).

A major advance in nuclear spectroscopy has been the determination of properties for well-separated low-lying levels. Transitions between such levels are of two types: 1) gamma-ray transitions, where a photon is radiated with energy equal to the difference of excitation energies; and 2) internal conversion transitions, where an orbital electron is emitted from the atom with an energy equal to the difference of excitation energies minus the atomic binding energy of the electron. The intensity ratio of these two types of de-excitation is called the Internal Conversion Coefficient (ICC). After the construction of an energy level diagram using gamma singles and coincidence spectra, several interesting features about the decay scheme are yet to be determined: 1) the nuclear spin of each level; 2) the relative parities of the levels; 3) the nuclear matrix elements; and 4) the nuclear electromagnetic moments. The ICC's can be used to determine the first and second and in some cases the third of these four parameters (16).

The energy levels for the decay of ^{140}Xe have been determined by Schick et al. (19). At the end of his paper he states: "Further speculations may be made concerning the spins of levels, based on the occurrence or lack of occurrence of gamma-ray transitions. However, firm assignments cannot be made until more experimental data are available, especially concerning internal conversion coefficients." Specifically, there are sixteen energy levels with energy less than 700 keV, but only twelve of these can be explained on the basis of two-quasiparticle states involving the lowest lying shell-model orbitals. Information concerning the spins and parities of these levels is needed to determine possible configurations

for these levels. The ICC measurements reported in this work constitute a response to the need presented in the work of Schick et al. (19).

II. EXPERIMENTAL FACILITY

A. The TRISTAN On-Line Isotope Separator System

The facility used in this experiment consisted of the Ames Laboratory Research Reactor, the "TRISTAN" isotope separator on-line to the reactor, a moving tape collector (MTC) and various detectors and electronics.

The Ames Laboratory Research Reactor is a heavy water moderated, enriched ^{235}U , 5 Megawatt (thermal) reactor (20). The fissioning sample is placed in an external beam of neutrons with a flux of about 3×10^9 neutrons/cm²/sec and is contained in a cylindrical aluminum can approximately 3 cm deep and 9 cm in diameter. In the can are several shallow trays containing approximately 6.09 gm of fully enriched ^{235}U in stearate form (21). The stearate form is used because of its emanation properties for the noble gases (nearly 100% emanation in 1 second at room temperature) (22,23). The emanated gaseous fission products are introduced into the isotope separator through a transport line of length 2 m with an average transport time of 1 to 2 seconds (24). The ion source discharge is supported by a "sweep" gas containing approximately 1% stable Kr, 1% stable Xe and 98% stable He, which may also aid in reducing the transport time.

The isotope separator itself has been described previously in several publications (21,24,25,26). Therefore, only a brief description will be given here. The fission products, along with the "sweep" gas, are ionized in an ion source. The non-ionized molecules are removed from the system by differential pumping. The ionized beam is then accelerated through 50 kV and focused by a system of two electrostatic lenses. The focused beam is introduced into a 1.6-m, 90° analyzing magnet. In a collector box,

situated at the focal plane of the magnet where the ion beams are fully dispersed, a set of slits selects the mass of interest from the other mass components of the beam. The beam is position stabilized in the focal plane by means of a set of parallel copper strips. A convenient mass ion beam can be centered between the strips, and as it drifts from the centered position, a differential current picked up by the strips is converted to a correction voltage to be applied to the acceleration voltage, bringing the beam back into position. The mass-selected beam, also stabilized, passes through the defining slits and into a switching magnet. The switching magnet further focuses and mass separates the beam while directing it into a moving tape collector (MTC). Figure 2 shows the layout of the TRISTAN system.

The MTC contains approximately 610 m of 0.025 mm thick aluminized mylar tape. The tape makes a 45 degree angle with the beam, which has a shape of 6 - 8 mm high by 1 mm wide (24). There are six detector ports on the MTC, 4 external and 2 internal to the vacuum. One of the internal ports and two of the external ports surround the tape on three sides at the position of beam deposition. The other three ports are located approximately 0.45 m "downstream" in the tape motion. The first three ports are for use in examining "parent" or short-lived "daughter" activities while the other ports are for the study of longer-lived "daughter" activities. The MTC is thus used for isobaric separation of the activities in the decay chain of the collected sample. To accomplish this most effectively, the MTC can be operated in any of three modes. The "parent" activity can be emphasized by moving the tape continuously at a speed

Figure 2. A block diagram of the TRISTAN facility

determined to optimize the isobaric separation and retain a good count rate. To study short-lived "daughter" activities, the MTC is operated in the sequential mode with collect, delay, accumulate and transport times counted sequentially. This latter mode is used with the detectors mounted on the upper ports. To study the longer-lived "daughter" activities more efficiently, the detectors are moved to the downstream ports and the MTC is operated in the high-duty factor (HDF) mode. In this mode, data can be accumulated at the lower ports while a new sample is being collected at the upper port. Times used for operation of the MTC to optimize both the separation and the count rate of a desired "daughter" activity were determined by use of the program ISOBAR written by J. H. Norman, (see Appendix C). In the coincidence experiments reported here, a parent-daughter activity mixture of up to 10% was allowed in order to enhance the count rate. In the singles experiments, a mixed activity ratio of less than 3% was usually maintained.

B. Detectors and Electronics

During the course of this work, three detectors were used: a plastic scintillator, a Ge(Li) detector, and a Si(Li) detector. The plastic scintillator was used in coincidence with the Ge(Li) detector for the beta-gamma coincidence experiments, or was used alone to measure the beta singles spectra. The Si(Li) detector was used to measure the ICC's for the decay of ^{140}Xe .

The plastic scintillator is a well-type cylindrical scintillator made of Pilot B plastic. Figures 3 and 4 show the plastic scintillator mounted on the upper internal port of the MTC. The well is in the shape of a

Figure 3. The MTC and plastic scintillator with the source holder in position

Figure 4. The MTC and plastic scintillator with the tape in position

truncated cone with an entrance diameter of 1.9 cm and a depth of 2.3 cm. The detector is situated so that the source is at the vertex of the cone, a distance of 5.7 cm from the front of the well. The solid angle subtended by the well through the defining aperture is 0.7% of 4π steradians. The side and front surfaces of the scintillator are coated with a titanium dioxide reflective coating, and the scintillator is coupled to an EMI 9708 KR photomultiplier. The effect of the well is to greatly reduce the backscattering out of the detector which it does at the expense of producing a quadratic energy calibration curve. The response of the scintillator to monoenergetic electrons has been measured as a function of energy, with the resulting response function used to determine the true beta spectrum from the measured spectrum. The major distortions of the spectrum due to the response of the detector result from the finite resolution of the detector and the back-scatter tail. The resolution causes the spectrum to extend beyond the maximum energy and the back-scatter tail causes more events to appear at low energy than normal. Figure 5 shows the measured response of this plastic scintillator. Further details in the description of this scintillator have been published recently (27).

The Ge(Li) detector is an ORTEC 60 cm³ coaxial type detector. The FWHM resolution is approximately 2.8 keV for the ⁶⁰Co 1.33-MeV transition and the peak-to-Compton ratio is 28:1. The efficiency of the detector is 11% compared to a 7.6 cm by 7.6 cm NaI(Tl) detector. The detector was situated approximately 5 cm from the source and subtended a solid angle approximately 2% of 4π steradians. For the beta-gamma coincidence

Figure 5. Response of the plastic scintillator

measurements, the Ge(Li) detector was used for gating purposes only. In the measurement of the ICC's in the decay of ^{140}Xe , it was used to measure directly the coefficient for several of the more strongly converted gamma ray transitions.

The Si(Li) detector used in the ICC measurements was manufactured by Nuclear Equipment Corporation. It has an active area of 300 mm^2 and an active depth of 3 mm (approximately the depth needed to stop a 1.5-MeV electron in silicon). The full-energy efficiency of the detector for electrons was measured from 28 to 1500 keV, using $^{85\text{m}}\text{Kr}$, $^{180\text{m}}\text{Hf}$ and $^{110\text{m}}\text{Ag}$. The relative conversion electron intensities used to determine this efficiency for the decay of $^{110\text{m}}\text{Ag}$ were measured with a magnetic spectrometer by Moragues et al. (28). The conversion electron intensities for $^{180\text{m}}\text{Hf}$ were measured by Edwards and Boehm (29). The conversion electron intensities for the two transitions in $^{85\text{m}}\text{Kr}$ were measured in a magnetic spectrometer by Wohn et al. (30). The $^{85\text{m}}\text{Kr}$ calibration source was produced on-line and was also used for the solid angle and live-time corrections in the ICC measurements. The detector is housed in a portable cryostat that can be mounted on top of the MTC or can be used off-line. The cryostat has its own vacuum system provided by a Varian 2 liter/sec vac-ion pump. The pressure at the ion pump is approximately 0.2 μTorr while the detector is off-line. While it is used on-line, it is pumped on by a 5-cm oil diffusion pump to maintain a vacuum of 6 - 10 μTorr with a liquid nitrogen cold trap maintained between the pump and the detector to trap any oil vapors and prevent their deposition on the detector. The resolution of the detector for electrons ranges from approximately

2.0 keV at 100 keV to about 3.0 keV at 1 MeV. Figures 6 and 7 show the Si(Li) detector in position on the MTC. Figure 6 shows the absorber wheel which can be used to eliminate the electrons and make possible the identification of the photon spectrum in the detector. Figure 7 shows a special mating flange used in place of the absorber wheel assembly to position the detector closer to the tape and hence increase the solid angle subtended.

Calibration of the plastic scintillator was done using the conversion peaks and end-point energies from 9 different on- and off-line sources, shown in Table 1. The off-line sources were placed into the vacuum in the same place as the on-line sources by using a source rack. Figure 3 shows the tape moved out of the way and the source rack in position in front of the plastic scintillator. Figure 4 shows the tape in position during running conditions. The sources were air-evaporated onto thin aluminized Mylar.

The functional form for the energy calibration of the plastic scintillator shows a distinct quadratic behavior at low energies that is due, it is believed, to the conical well, which causes the light collection efficiency of the plastic-photomultiplier system to be energy dependent (31). Therefore, the energy calibration curve has two regions: a linear region for higher energies ($E > \text{about } 3 \text{ MeV}$) and a quadratic region for the lower energies. The two regions are joined smoothly at a cross-over energy. Figure 8 shows a typical energy calibration curve. The solid line is the actual calibration curve and the dashed line is the low-energy extrapolation of the linear portion of the curve. The empirical

Figure 6. The MTC and Si(Li) detector with bellows contracted

Figure 7. The MTC and Si(Li) detector with bellows expanded

Figure 8. Typical energy calibration for the plastic scintillator

functional form for the calibration is:

$$\begin{aligned}
 E &= SN + D & N &\geq N' \\
 &= SN + D \left[1 - \left(\frac{N' - N}{N'} \right)^2 \right] & N &\leq N'
 \end{aligned}$$

The three calibration parameters are:

S the slope for the linear region

N' the cross-over channel

D the intercept for the linear region.

To determine the energy calibration for a given set of calibration energies, the data are first compressed to 128 channels and plotted using the computer program CARD (see Appendix C). The end-point energies for the various calibration spectra are estimated from the plots. The peak channels for the conversion peaks are measured by expanding the peak, drawing a smooth curve through the data, bisecting several lines drawn from one side of the peak to the other and then drawing a smooth curve through the centers of the lines. In this manner, the centroid of the conversion peaks can be determined to within a few tenths of a channel. This corresponds to an energy uncertainty of less than 10 keV. The values for the centroids and the initial estimates for the end-point channels are used as input for a Conversational Programming System (CPS) routine called CALIB (see Appendix C). CALIB fits the data to find the three calibration parameters. The calibration beta spectra are then fit using FERMI (see

Appendix C) assuming the initial values for the calibration parameters. The output from FERMI gives a better estimate for the end-point channels which are subsequently used as input for a new run of CALIB. The procedure is iterated until the end-point channels as fit by FERMI change by no more than 0.2 channels (approximately 6 keV). If the initial estimates for the end-point channels are good, usually only 3 or 4 iterations are required.

The energy calibration for the Ge(Li) detector need only be approximate as the spectra are all known. The Si(Li) detector also needs only an approximate energy calibration, as the spectrum of ^{140}Xe also is well known (19). However, in order to use the gamma-ray-to-conversion-electron intensity ratio method to measure the internal conversion coefficients, the solid angle and live-time corrections to the count rates must be made carefully. The conversion coefficients for the decay of $^{85\text{m}}\text{Kr}$ have been measured using the normalized conversion-peak-to-beta-group method by Wohn et al. (30). Since this source can be produced on-line in the TRISTAN system, it is a convenient calibration source for the Si(Li) - Ge(Li) detector system. This calibration source provides both the intensity correction factor and an approximate energy calibration for both the Si(Li) and Ge(Li) detectors.

The electronics used in the beta-gamma coincidence experiment are common to many types of coincidence measurements. A block diagram showing the coincidence electronics is given in Figure 9. The Timing Filter Amplifiers are ORTEC model 454, the Constant Fraction Timing Discriminators are ORTEC model 453, and the Time to Pulse Height Converters are

Figure 9. Block diagram of electronics used for beta-gamma coincidence

ORTEC model 437. The coincidence pulse is used to gate the TMC model 217A Analog-to-Digital Convertors (ADC). The timing window for the coincidence system was typically 25 nsec.

The experimental data is then processed by a two parameter format selector into a buffer tape unit. The buffer tape unit stores the data in a 4096 by 4096 array by sequentially recording them onto a magnetic tape. In this manner, all coincidence events are stored and the data can be examined at a later time.

After all the data were collected, they were read back into the memory of a multi-channel analyzer in one of a number of modes. One mode allowed examination of the gamma spectrum in order to determine which gamma rays to use as gates. In this mode, coincidence spectra of both detectors were read back in. However, if the gamma rays used as gates were already known, these gates were set up immediately (by indicating the lower and upper channel limits for each gate on the band selector) and the tapes played back in the sorting mode. In this mode, up to 16 gates or bands could be set up. The output from the plastic scintillator in time coincidence with the gamma ray indicated by gate no. 1 was placed into the memory of the multi-channel analyzer in sub-location 1. The spectrum from the plastic scintillator which is in coincidence with gate or band no. 2 was placed into sub-location 2, etc. Typically, an additional gate was set for each gamma-ray gate, the same size as the peak gate and just higher in energy. The gate registered the beta spectrum in coincidence with the Compton events from higher-energy transitions in the gamma spectrum and was subtracted out to determine the true coincidence spectrum. In addition, the spectrum was also corrected for the gamma-ray

response of the plastic scintillator (see Appendix B).

The electronics for the beta singles experiment is basically the same as for the energy side of the coincidence set-up. The only difference is that the ADC is operated in the singles mode instead of the coincidence mode.

The electronics set up for the Si(Li) detector used for the measurement of the ICC's is similar to the singles set-up for beta singles. However, the output from the Si(Li) detector is too slow for the TMC 217A ADC. Therefore, a Geoscience model 8050 ADC was used, to make the peak shape more nearly Gaussian for the output of the Si(Li) detector.

Table 1. Beta-ray calibration data

Source	Beta-ray energy in MeV	Percent branching to daughter energy level in MeV	References
^{85m}Kr	0.291 ^a		32
^{137}Cs	0.630 ^a		32,33
^{85m}Kr	0.840 $\pm$ 0.002	100% to 0.151	30,32
^{207}Bi	0.991 ^a		32
^{32}P	1.707 $\pm$ 0.001	100% to g.s.	32,34,35,36
^{141}La	2.430 $\pm$ 0.030	98% to g.s. 2% to 1.37	32,37,38
^{144}Ce	2.990 $\pm$ 0.006	97.7% to g.s. 1.3 to 0.695 1.0% to 2.184	32,39,40
^{137}Xe	4.090 $\pm$ 0.050	70% to g.s. 30% to 0.456	41,42,43
^{38}Cl	4.913 $\pm$ 0.005	57.6% to g.s. 11.1% to 2.168 31.3% to 3.810	44
^{88}Rb	5.170 $\pm$ 0.080	76% to g.s. 4% to 1.84 14% to 2.73	32,45,46,47

^aWeighted average of K, L, and M internal conversion electron energies.

III. EXPERIMENTAL RESULTS

A. Beta Decay Energies

Two different methods were used to measure beta decay energies. The most frequently used method was a beta-gamma coincidence method. In this method, both the plastic beta scintillator and the Ge(Li) gamma detector were used in time coincidence. As the data were being taken, the response to gamma rays of the plastic scintillator was corrected for by a method described in Appendix B.

The gamma-ray study of Cook (48) indicates that the beta decay of ^{141}Cs proceeds mainly to the ground state of ^{141}Ba . Thus, beta-gamma studies for this activity would result in low counting rates, and the data were taken in the singles mode. The singles beta spectrum measurement also made it possible to measure the ground-state branching for this decay. The data taken in the singles mode were corrected for the response of the plastic scintillator to gamma rays in the same way that the calibration data were (see Appendix A).

After taking the data, the previously taken gamma spectrum was examined for each decay studied. The strongest gamma-ray transitions in the coincidence spectrum were used as "gates" and the beta spectra in coincidence with them were sorted out by the buffer tape unit. These "gated" spectra were plotted and the end-point energy for each was estimated. The computer program FERMI (see Appendix C) can fit a spectrum made up of 5 individual beta groups provided the relative intensity of each group is held fixed relative to the most energetic group. In addition, the end-point energy differences must be fixed. This information can be

determined from the gamma-ray energy level scheme. The gamma-ray intensity balance for each level in the "daughter" nucleus was calculated to determine the relative beta feeding to each level. The composition of each spectrum was determined as follows: the relative intensity of beta group "i" in the spectrum which is in coincidence with a gamma ray depopulating level "j" is equal to the relative beta feeding to level "i" times the fraction of the gamma-ray intensity leaving level "i" that populates level "j." The "gated" spectra were then fit and the end-point energy for each spectrum was measured using the computer program FERMI. The method described above was used to analyze all of the beta-gamma spectra except for the spectrum in coincidence with the 0.3595 MeV gamma-ray transition following the beta decay of ^{142}Cs . This spectrum and the beta-singles spectrum of the decay of ^{141}Cs were analyzed using the computer program SPEC. (see Appendix C). No assumptions about the composition of the spectrum were necessary for this program. A reasonable region of fit for the most energetic beta group was determined by looking at the plot of the data after the effects of the detector response had been removed in an unfolding technique. This "outer" group was fit and the end-point energy and amplitude of the beta group were measured. The "outer" group was then subtracted from the spectrum and the resulting spectrum was examined to determine the region of fit for the next lower group in energy. These two groups were fit simultaneously, their end-point energies and amplitudes were measured and both were subtracted from the original spectrum. This process was iterated until the residual spectrum indicated that there were no more groups left.

The beta decay energies, or Q-values, were measured for the following seven nuclei: ^{140}Xe , ^{140}Cs , ^{141}Xe , ^{141}Cs , ^{141}Ba , ^{142}Xe , and ^{142}Cs . With the exception of ^{141}Cs , all energies were determined from beta-gamma coincidence measurements. Tables 2 through 7 list the results of these measurements. In each table except Table 4, the beta-gamma results are listed, including the gating gamma ray, the energy level in the daughter nucleus, the groups used in the fitting of each spectrum, the relative intensity of each group, the individual measurement of the beta decay energy (the sum of the end-point energy of the outer group and the energy of the level to which it decays) as determined using the previously determined decay schemes, and the uncertainty in the individual beta decay energy.

The MTC was run in the continuous mode at a tape speed of 0.2 cm/sec for the study of the decay of ^{140}Xe . According to ISOBAR, this speed yielded an activity composition of 96.6% ^{140}Xe and 3.1% ^{140}Cs . The beta spectra in coincidence with thirteen gamma-ray transitions were used to determine the beta-decay end-point energy for the decay of ^{140}Xe , according to the decay scheme determined by Schick et al. (19). These thirteen gamma-ray transitions represent de-excitations from six levels in ^{140}Cs , with seven of the transitions de-exciting the highly beta-fed 1.4276-MeV level in ^{140}Cs . The weighted sum of the several determinations of the Q-value for the decay of ^{140}Xe is 4.06 ± 0.06 MeV. Table 2 shows the results of this analysis. Figure 10 shows the FERMI fit to the beta spectrum in coincidence with the 0.744-MeV transition in this decay. The figure serves as an example of the fitting to a single beta group in this study.

Table 2. Results for ^{140}Xe beta-gamma coincidence

Gating Transition (MeV)	Level Depopulated (MeV)	Groups Included in Fit		Beta Decay Energy (MeV)
		Level (MeV)	Relative Intensity %	
0.1125	0.1125	1.2892	11.8	4.119 ± 0.036
		1.4276	88.2	
0.1185	0.1185	1.1371	4.2	4.116 ± 0.034
		1.2892	1.5	
		1.4276	94.3	
0.2120	0.2120	1.1371	31.2	3.998 ± 0.059
		1.2892	25.0	
		1.4276	43.8	
0.4387	0.4387	1.2892	12.1	4.067 ± 0.050
		1.4276	87.9	
0.5573	0.6220	1.4286	100	3.972 ± 0.040
0.6220	0.6220	1.4276	100	3.953 ± 0.034
0.6534	1.4276	1.4276	100	4.037 ± 0.039
0.7741	1.4276	1.4276	100	4.001 ± 0.040
0.8055	1.4276	1.4276	100	4.082 ± 0.032
0.8798	1.4276	1.4276	100	4.016 ± 0.053
0.9890	1.4276	1.4276	100	4.040 ± 0.047
1.3091	1.4276	1.4276	100	4.100 ± 0.034
1.4137	1.4276	1.4276	100	4.147 ± 0.033
Average				4.06 ± 0.06

Table 3. Results for ^{141}Xe beta-gamma coincidence

Gating Transition (MeV)	Level Depopulated (MeV)	Groups Included in Fit		Beta Decay End- Point Energy (MeV)
		Level (MeV)	Relative Intensity %	
0.11876	0.11876	0.467	13.9	6.049 ± 0.139
		0.644	1.1	
		0.979	1.4	
		1.097	83.6	
0.1876	0.1876	0.467	13.9	5.756 ± 0.166
		0.644	1.1	
		0.979	1.4	
		1.097	83.6	
0.3619	0.467	0.644	100	5.809 ± 0.374
0.3694	0.369	1.097	100	5.960 ± 0.433
0.4593	1.556	1.556	100	6.023 ± 0.081
0.4679	0.467	1.556	100	6.108 ± 0.122
0.5384	0.644	1.097	100	5.837 ± 0.082
0.9094	1.097	1.097	78.5	5.981 ± 0.084
		1.556	21.5	
Average				6.0 ± 0.1

Table 4. Results for ^{141}Cs beta-single

Energy Level (MeV)	End-Point Energy (MeV)	Relative Intensity (%)	Beta Decay Energy (MeV)
0.0	4.98 ± 0.08	50.0 ± 0.3	4.99 ± 0.08
1.66	3.32 ± 0.04	12.3 ± 0.1	
2.81	2.17 ± 0.03	16.5 ± 0.1	
3.54	1.44 ± 0.02	21.2 ± 0.1	

Table 5. Results for ^{141}Ba beta-gamma coincidence

Gating Transition (MeV)	Level Depopulated (MeV)	Groups Included in Fit		Beta Decay End-Point Energy (MeV)
		Level (MeV)	Relative Intensity (%)	
0.190	0.190	0.190	44.4	2.924 ± 0.039
		0.467	55.6	
0.277	0.467	0.467	100	3.055 ± 0.041
0.344	0.648	0.648	100	3.002 ± 0.045
0.467	0.467	0.467	100	3.086 ± 0.052
Average				3.01 ± 0.06

Table 6. Results for ^{142}Xe beta-gamma coincidence

Gating Transition (MeV)	Level Depopulated MeV)	Groups Included in Fit		Beta Decay Energy (MeV)
		Level (MeV)	Relative Intensity (%)	
0.538	1.195	1.195	100	5.081 $\pm$ 0.062
0.571	0.657	0.657	81.0	4.793 $\pm$ 0.054
		1.195	19.0	
0.618	0.657	0.657	81.0	5.016 $\pm$ 0.058
		1.195	19.0	
0.644	0.657	0.657	81.0	4.807 $\pm$ 0.060
		1.195	19.0	
0.657	0.657	0.657	81.0	4.904 $\pm$ 0.061
		1.195	19.0	
Average				4.9 $\pm$ 0.1

Table 7. Results for ^{142}Cs beta-gamma coincidence

Gating Transition (MeV)	Level Depopulated (MeV)	Groups Included in Fit			Beta Decay Energy (MeV)
		Level (MeV)	Relative Intensity (%)		
0.360	0.360	1.32	18.3		6.91 ± 0.08
		2.65	33.4		
		3.54	33.9		
		3.16	14.4		
0.966	1.326	1.326	100		6.806 ± 0.09
1.175	1.535	1.535	100		6.635 ± 0.144
1.326	1.326	1.326	100		6.951 ± 0.091
Average					6.9 ± 0.1
					(all 4)

Figure 10. Measured spectrum and Kurie plot for the beta spectrum in coincidence with the 0.774-MeV gamma ray in the beta decay of ^{140}Xe and the FERMI fit to each

For the study of the decay of ^{140}Cs , the MTC was run in the sequential mode with the following time settings:

COLLECT TIME	40 sec
DELAY TIME	50 sec
ACCUMULATE TIME	80 sec

These conditions gave an activity composition, as calculated from ISOBAR, of 9% ^{140}Xe and 91% ^{140}Cs . In this decay, only one gamma-ray gate was found to produce sufficient statistics for proper analysis. This gate was the 0.602-MeV transition from the first excited state to the ground state in ^{140}Ba . The decay scheme is not yet published, but has been preliminarily determined by W. C. Schick (49). The beta decay energy for ^{140}Cs , based on the result of this one spectrum, is 5.8 ± 0.1 MeV.

Six gates, which are de-excitations from four levels in ^{141}Cs , were used to determine the beta decay energy for ^{141}Xe . The preliminary decay scheme used to determine the composition of various coincidence spectra in this decay was determined by J. W. Cook (48). The Q-value resulting from this measurement is 6.0 ± 0.1 MeV. For this experiment, the MTC was used in the continuous mode with a tape speed of 0.2 cm/sec. These conditions, according to ISOBAR, yielded an activity composition of 92% ^{141}Xe and 8% ^{141}Cs . Figure 11 shows the two-group FERMI fit to the beta spectrum gated by the 0.909 MeV transition in this decay. It was assumed that two beta groups make up the spectrum: 1) the group feeding the 1.097 MeV level in ^{141}Cs (78%); and 2) the beta group feeding the 1.556 MeV level in ^{141}Cs (22%) where the percentages indicate the fraction that the particular group contributes to the total spectrum. Table 3 lists

Figure 11. Measured spectrum and Kurie plot for the beta spectrum in coincidence with the 0.909-MeV gamma ray in the beta decay of ^{141}Xe and the FERMI fit to each

all the beta-gamma results for this decay.

According to the study in progress by Cook (48), the decay of ^{141}Cs should proceed mainly to the ground state of ^{141}Ba . In the light of this study, a decision was made not to attempt a beta-gamma coincidence experiment on this decay and instead perform a beta singles experiment. The spectrum was corrected for the gamma response of the plastic scintillator in the same way as for the calibration sources, namely using two absorbers (see Appendix A). The mode of operation for the MTC in this singles measurement was chosen to eliminate as much as possible the ^{141}Xe activity, since it has a beta decay energy larger than that of ^{141}Cs (5.86 MeV as opposed to about 5.0 MeV). In order to do this, the MTC was run in the sequential mode with the following time settings:

COLLECT TIME	40 SEC
DELAY TIME	15 SEC
ACCUMULATE TIME	40 SEC

With these time settings, the activity composition predicted by ISOBAR is 94% ^{141}Cs and 6% ^{141}Ba . Although the 6% ^{141}Ba contamination is somewhat high for a singles experiment, the decay energy for ^{141}Ba had been previously measured to be 3.03 MeV. This decay energy is 2 MeV lower than the expected 5.0 MeV Q-value for ^{141}Cs . Therefore it was felt that these data would be sufficient to determine the ^{141}Cs decay energy using at least the top half of the spectrum. The spectrum was analyzed using a computer program SPEC. Analysis of the singles measurement indicated a ground state feeding of about 50% and a beta decay energy of 4.99 ± 0.08 MeV. In the fitting procedure, four major groups were found to contribute

to the total spectrum. These are listed in Table 4 and the spectrum fit is shown in Figure 12. In the correction for gamma rays detected in the plastic scintillator, the two-absorber technique could have a dependence on activity collection rate variations, as discussed in Appendix A. To test the effect of such variations, caused by relatively unstable separator operation, two data sets of singles measurements on ^{141}Cs decay were compared. One set was obtained under very constant operating conditions, while for the other set, the separator was not operating well. Comparison of the decay energies for the two sets revealed the effect to be small, within the quoted experimental uncertainties (5.07 ± 0.08 MeV for unstable conditions, compared to 4.98 ± 0.08 MeV for the stable conditions).

Four gates were used to determine the beta decay energy for ^{141}Ba decay, representing transitions from three of the low-energy levels in ^{141}La . The MTC was run in the HDF mode for this study with the following time settings:

COLLECT TIME	2360 SEC
DELAY TIME	310 SEC
ACCUMULATE TIME	2670 SEC

This yielded an activity composition of 81% ^{141}Ba and 19% ^{141}La . This unusually high contamination was accepted in order to increase the count rate. The resulting decay energy is 3.01 ± 0.06 MeV, using the gamma-ray decay scheme determined by Cook (48). Table 5 lists the beta-gamma results for this decay.

The gamma-ray decay schemes for the decays of ^{142}Xe and ^{142}Cs were taken from the work of Larsen et al. (50). Since the half-lives of these

Figure 12. Measured spectrum and Kurie plot for ^{141}Cs singles showing the SPEC fit to each

two isobars are 1.24 sec and 1.67 sec, respectively, a separation of the two during the coincidence experiment was not attempted. The conditions required to provide effective separation for such similar half-lives reduces the available source activity to an intolerably low level for a coincidence experiment. The MTC was run in the continuous mode with a speed of 0.2 cm/sec, which resulted in a sample activity composition of 59% ^{142}Xe , 40% ^{142}Cs and 1% ^{142}Ba . A total of five gates were used to determine the beta decay energy for the decay of ^{142}Xe . The weighted average of the values obtained in this measurement is 4.9 ± 0.1 MeV. Table 6 lists the beta-gamma results for this decay.

Four gates were used to determine the beta decay energy for the decay of ^{142}Cs . The weighted average of the analyzed results is 6.86 ± 0.10 MeV. Using only three gates (excluding the 1175-keV gate, which is uncertainly placed in the decay scheme) the weighted average of the resulting decay energy values is 6.89 ± 0.06 MeV. The two values are well within the uncertainties indicated. Figure 13 shows the SPEC output for the fit to the spectrum in coincidence with the 0.360 MeV transition in this decay. The amplitudes and end-point energies of the four indicated groups were allowed to vary. These groups are listed in Table 7 along with the other results for this decay.

A compilation of all the beta decay end-point energy results obtained in this work is shown in Table 8, which includes the decaying nucleus, the theoretical prediction of the end-point energy according to the mass relations developed by Garvey et al. (10) and Seeger (9), the previously measured or predicted (*) decay energy compiled by Wapstra and Gove (2),

Figure 13. Measured spectrum and Kurie plot for the beta spectrum in coincidence with the 0.360-MeV gamma ray in the decay of ^{142}Cs showing the SPEC fit to both

and the decay energy according to this work with the number of gates used in this work to measure the energy.

Table 8. Beta decay energy results

Decaying Nuclear	Predicted Energy			Results this Work	
	Garvey et al. (10) (MeV)	Seeger (9) (MeV)	Wapstra and Gove (2) (MeV)	Energy (MeV)	# Gates Used
^{140}Xe	3.58	3.4	4.3	4.06 ± 0.06	13
^{140}Cs	6.12	5.1	5.7 ± 0.1	5.8 ± 0.1	1
^{141}Xe	5.85	5.5		6.0 ± 0.1	8
^{141}Cs	4.97	4.1	5.1	4.98 ± 0.08	singles
^{141}Ba	3.02	2.7	3.0 ± 0.1^a	3.01 ± 0.06	4
^{142}Xe	4.34	4.3		4.9 ± 0.1	5
^{142}Cs	7.24	6.2	6.7	6.89 ± 0.06	3

^aThis value is from a previous measurement.

B. Results for the ICC Measurements for the Decay of ^{140}Xe

The internal conversion coefficients for eighteen gamma transitions associated with the decay of ^{140}Xe were measured using the normalized gamma-to-conversion-electron ratio method and the resulting multipolarities for the transitions were assigned. $^{85\text{m}}\text{Kr}$ was deposited for thirty minutes in the MTC and then a sample of $A = 140$ activity was deposited on top of it. The Si(Li) and Ge(Li) detectors were used in a dual singles mode to count the gamma and conversion electron spectra simultaneously. During this dual singles experiment, the tape in the MTC was not moved, which allowed both ^{140}Xe and ^{140}Cs activities to build up for the 90-minute duration of the measurement. Figures 14 and 15 show the spectra taken with the Si(Li) and Ge(Li) detectors, respectively, during this part of the experiment.

Following the dual singles, a 16-hour singles experiment was performed for the purpose of clarifying the electron spectrum. For this measurement, the Si(Li) detector alone was used and the MTC was operated in the HDF mode with the following time settings:

Collect time	28 sec
Delay time	0 sec
Accumulate time	28 sec

As the data were taken during this run, they were read out onto magnetic tape periodically to avoid analyzer memory overflows. Figure 16 shows the spectrum of the Si(Li) detector obtained for this longer singles run. At three times during the long singles run, an absorber was placed in front of the Si(Li) detector to screen out the electrons and record

Figure 14. Electron spectrum for dual singles A=140 and ^{85m}Kr

Figure 14 (Continued).

Figure 15. Gamma-ray spectrum for dual singles A=140 and ^{85m}Kr

Figure 15 (Continued).

Figure 16. Electron spectrum for the decay of ^{140}Xe

Figure 16 (Continued).

the photon spectrum from the Si(Li) detector.

The resulting spectra were analyzed using the computer programs PEAKFIND and SKEWGAUSS (see Appendix C) and the relative intensities of the gamma rays and conversion electrons were measured. These intensities were then corrected for the relative photo-peak and full-energy peak efficiencies of the Ge(Li) and Si(Li) detectors. The measured relative efficiency for the Si(Li) detector is shown in Figure 17. The corrected intensities were combined with the published relative intensities for the decay of ^{140}Xe determined by Schlick et al. (19) to determine the ICC's for the transitions in the following manner: 1) the solid-angle and live-time correction was made using the known ICC's for the 151-keV and 304-keV transitions in $^{85\text{m}}\text{Kr}$ together with the theoretical ICC for the 602-keV transition in the decay of ^{140}Cs (2^+ to 0^+ first excited state transition assumed to be pure E2); 2) the renormalization factors for the gamma and conversion electron intensities (to make them correspond to the units of the dual singles run) were determined using several of the stronger transitions in each spectrum and taking a weighted average of the results; and 3) the intensities were corrected for possible contamination from photons within the Si(Li) spectrum and for photons or conversion electrons resulting from a noticeable amount of ^{139}Xe hydride ion contamination. The ICC's are then calculated using the relation

$$\alpha = \bar{\epsilon} \frac{I_{\text{em}}}{I_{\gamma\text{m}}}$$

where I_{em} is the conversion electron intensity measured in the long singles run, $I_{\gamma\text{m}}$ is the normalized relative gamma intensity as measured

Figure 17. Measured relative full electron energy efficiency curve for the Si(Li) detector

by Schick et al. (19), and $\bar{\epsilon}$ is the combined intensity ratio correction factor incorporating the solid angle and live-time corrections as well as the renormalization of the gamma and conversion electron intensities. For the measurement reported in this work, the value of $\bar{\epsilon}$ was $(3.74 \pm 0.54) \times 10^{-5}$. The relative gamma intensities and the corresponding conversion electron intensities are listed in Table 9. After the ICC's were determined, they were compared with the theoretical coefficients tabulated by Hager and Seltzer (15) to determine the possible multipolarity for each transition. Due to the rather large experimental errors, due mainly to the large continuous beta background upon which the conversion electron peaks were situated, it was not possible in most cases to make an unambiguous assignment on the basis of comparison of the predicted (15) and observed values. Mixtures were determined disregarding the ICC uncertainties and should be regarded only as illustrative, not fact.

The conversion electron peak at 45.5 keV is complex, containing both K-shell conversion electrons for the 80-keV transition and L-shell conversion electrons for the 50-keV transition. Therefore, an unambiguous determination for the conversion coefficient for either transition was not possible. Instead, possible combinations of E1, E2, M1 and M2 coefficients were assumed for the two transitions and the predicted conversion electron intensities were compared with the measured intensity, which agreed well with the intensity predicted if both transitions are assumed to be pure M1. These transitions are thus assigned a multipolarity of M1 with a possible admixture of E2.

The conversion electron peak at 70-keV has components from K-shell

Table 9. Gamma and conversion electron intensities for decay of ^{140}Xe

Gamma Energy (keV)	Relative Gamma Intensity	Relative Conversion Electron Intensity	Shell	Multi-polarity
50.6	8.3 ± 2.0	$(9.42 \pm 0.08) \times 10^5$ ^a	L	M1 (E2)
80.11	22.0 ± 2.2	$(9.42 \pm 0.09) \times 10^5$ ^a	K	M1 (E2)
103.0	4.8 ± 0.8	$(3.00 \pm 0.08) \times 10^5$ ^b	K	E2 (M1)
104.4	6.4 ± 1.0	$(3.00 \pm 0.08) \times 10^5$ ^b	K	E2 (M1)
112.52	18.5 ± 1.8	$(5.65 \pm 0.07) \times 10^5$ ^c	K	E2 (M1)
118.46	22.4 ± 2.2	$(3.20 \pm 0.07) \times 10^5$	K	M1 (E2)
167.26	6.2 ± 0.6	$(3.09 \pm 0.08) \times 10^4$	K	M1 (E2)
196.2	1.10 ± 0.25	$(1.89 \pm 0.10) \times 10^4$ ^d	K	E2 (M1)
198.1	2.8 ± 0.3	$(1.88 \pm 0.10) \times 10^4$ ^d	K	E2 (M1)
212.0	11.5 ± 1.2	$(4.47 \pm 0.06) \times 10^4$	K	M1, E2
		$(5.6 \pm 0.12) \times 10^3$	L	
276.99	2.8 ± 0.3	$(5.02 \pm 0.17) \times 10^3$	K	M1, E2
281.00	6.9 ± 0.7	$(1.07 \pm 0.10) \times 10^4$	K	M1, E2
389.97	7.3 ± 0.7	$(3.42 \pm 0.20) \times 10^4$	K	E2 (M1)
438.69	13.0 ± 1.3	$(6.20 \pm 0.11) \times 10^3$	K	M1 (E2)
557.26	25 ± 2	$(5.67 \pm 0.16) \times 10^3$	K	M1 (E2)
621.98	40 ± 3	$(5.79 \pm 0.14) \times 10^3$	K	M1, E2
653.40	24 ± 2	$(1.65 \pm 0.24) \times 10^3$	K	M1, E2
805.52	100	$(3.25 \pm 0.28) \times 10^3$	K	E1

^a Includes 50.6-keV L and 80.11-keV K conversion electrons.

^b Includes 103.0 keV K and 104.4-keV K conversion electrons.

^c Includes 112.52-keV K and 80-keV L, M conversion electrons.

^d Includes 196.2-keV K, 198.1-keV K and 167.26-keV L conversion electrons.

conversion electrons for both the 103.0- and 104.4-keV transitions. Under the assumption of E2 multipolarity for each of these transitions, the predicted beta to gamma intensity ratio is very close to that observed. Therefore, these transitions were assigned a multipolarity of E2 with a possible small admixture of M1.

The conversion electron peak at 79-keV consists of three electron peaks; the K-shell conversion electrons for the 112-keV transition, and the L- and M-shell electrons for the 80-keV transition. This rather large energy spread (5 keV) is due to the fact that the strong 112-keV K line lies between the weaker 80-keV L and 80-keV M lines. Assuming that the 80-keV transition is pure M1, the K conversion coefficient for the 112-keV transition is deduced to be 0.86 ± 0.07 which compares well with the predicted 0.846 for a pure E2 multipolarity. Therefore, this transition was assigned a multipolarity of E2.

The 118-keV transition has a measured K conversion coefficient of 0.53 ± 0.11 . The conversion coefficient for an assumed M1 multipolarity transition at this energy is 0.483, and for an E2 multipolarity, 0.719. Since the measured value lies between these values, this transition is assigned a mixed multipolarity of 78% M1 and 22% E2, but the error in the measured conversion coefficient would allow this mixture to vary from pure M1 to nearly 50% E2 admixture.

The K conversion coefficient for the 167-keV transition was measured to be 0.186 ± 0.036 . The conversion coefficients assuming M1(E2) multipolarity are 0.185 (0.235), which indicates that this transition is of almost pure M1 character. The mixture was calculated to be 90% M1 and

10% E2, but again the error is very large.

The conversion electron peak at 162 keV corresponds to the 196-keV K, 198-keV K and 167-keV L electrons. Assuming a pure M1 multipolarity for the 167-keV transition and using the residual intensity to predict the multipolarities for the remaining two transitions, it was determined that the intensity is closely predicted by assuming pure E2 multipolarities for both the other transitions.

The 212-keV transition K conversion coefficient was measured to be 0.127 ± 0.034 , which overlaps the predicted E2 coefficient of 0.108, as well as the predicted M1 coefficient of 0.0968. The 212-keV transition L conversion coefficient was measured to be 0.0185 ± 0.004 . The M1 (E2) L conversion coefficients for this transition are 0.0127 (0.0230). The K/L ratio for the measured peaks is 6.8, which lies between the predicted ratios of 4.7 and 7.0 for the E2 and M1 multipolarities respectively. Therefore, the 212-keV transition is assigned a mixed multipolarity of dominant M1 and admixed E2, since the K/L ratio favors the M1 assignment, while the K coefficient is consistent with either.

The K conversion coefficient for the 276-keV transition was measured to be 0.067 ± 0.017 . This value is about 6% too large (even including the error) to be for M1 multipolarity and 8% too large to be for E2 character. Therefore, the M1, E2 multipolarity assignment to this transition is not conclusive.

The measured K conversion coefficient for the 281-keV transition is 0.055 ± 0.012 . This value overlaps both the M1 (0.046) and E2 (0.044) values so a M1, E2 multipolarity mixture is assigned to this transition.

The K conversion coefficient for the 389-keV transition was measured to be 0.0175 ± 0.0047 . The values predicted for M1 or E2 character for this transition are 0.042 or 0.0161, respectively. Thus, this transition is nearly pure E2 with less than 10% possible admixture of M1.

The K conversion coefficient for the 438-keV transition was measured to be 0.0166 ± 0.0040 , compared to a predicted value for M1 (E2) multipolarity of 0.0146 (0.0114). Therefore, the 438 keV transition is assigned a multipolarity of M1 with a possible admixture of E2. The K conversion coefficient for the 557-keV transition was measured to be 0.00847 ± 0.00190 which overlaps nicely the value of the predicted M1 transition ICC of 0.00808. However, the error suggests a possible admixture of E2 (ICC = 0.00594) so the transition is assigned a multipolarity of M1(E2).

The measured K conversion coefficient for the 621-keV transition is 0.0054 ± 0.0012 . The M1 (E2) coefficient for this transition is 0.0061 (0.00449), and this transition is assigned a multipolarity of M1, E2 with nearly equal mixing of each. The K conversion coefficient for the 653-keV transition was determined to be 0.00256 ± 0.0007 . This value does not overlap with the predicted M1 or E2 coefficients of 0.0055 and 0.00396, respectively. Comparison with the predicted E1 and M2 coefficients is even worse. This transition is thus assigned a (tentative) multipolarity of M1 or E2. The K conversion coefficient for the 805-keV transition was measured to be 0.00121 ± 0.00040 . This overlaps well with the predicted value of 0.000958 for an E1 multipolarity, and this transition is thus assigned a multipolarity of E1. A summary of these ICC

results is given in Table 9.

In addition to measuring some ICC's for transitions in this decay, the log ft. value, or comparative half-life, for each of the beta-fed levels in ^{140}Cs was calculated using the intensities of the gamma transitions after correction for conversion processes. In this calculation, the decay energy found earlier was used, and beta branching to the ground state and first excited state in ^{140}Cs was neglected (it is not expected that such an assumption would introduce significant errors into the log ft values for beta transitions to the other states). The beta transition log ft values are summarized in Table 10.

Table 10. Calculated log ft values for beta decay to ^{140}Cs levels

Energy Level (MeV)	Beta Energy (MeV)	% Beta Feeding (%)	Log Ft
0	4.06	--	--
0.0139	4.05	--	--
0.0646	4.00	0.01	9.11
0.0801	3.98	8.4	6.15
0.1030	3.96	0.9	7.09
0.1125	3.95	--	--
0.1185	3.94	--	--
0.1490	3.91	--	--
0.2120	3.85	--	--
0.2233	3.84	--	--
0.2320	3.83	--	--
0.2949	3.77	0.3	7.52
0.3450	3.72	0.2	7.68
0.4386	3.62	--	--
0.5148	3.55	1.0	6.85
0.5479	3.51	--	--
0.6220	3.44	--	--
0.6532	3.41	2.8	6.34
0.7741	3.29	5.1	6.02
0.8002	3.26	0.7	6.89
0.9030	3.16	0.4	7.08
0.9652	3.09	0.6	6.86
0.9825	3.08	--	--
1.1371	2.92	4.2	5.89
1.2892	2.77	3.3	5.90
1.4276	2.63	71.0	4.47
2.2860	1.77	0.4	6.06
2.3244	1.74	0.8	5.72

IV. DISCUSSION

A. Beta Decay Energies

The beta decay energies determined in this work are compiled in Table 8 in the previous chapter. Included in this compilation are the predictions of the decay energies by the mass relations of Garvey et al. (10) and Seeger (9) and the mass systematics of Wapstra and Gove (2). The discrepancy mentioned earlier on the reported values for the decay energy of ^{141}Ba are apparently resolved, since the result of the present work (3.01 ± 0.06 MeV) agrees well with that of Fritze and Kennett (7). The weighted root-mean-square (rms) deviation of the decay energies listed in Table 8 from those predicted by Garvey et al. (10) is 0.39 MeV. The weighted rms deviation for the same comparison, using the Seeger mass formula (9), is 0.63 MeV. Thus, the predictions of Garvey et al. agree with the measured beta decay energies better than do those of Seeger. This is not surprising since Garvey et al. used the known beta decay energies for nearby masses as a means to directly predict the unknown masses, while Seeger attempted to modify the semi-empirical mass formula and used the known masses as data to determine the coefficients for his mass law. Therefore, since the beta decay energy is the relatively small difference between two much larger numbers, it could be expected that the deviation for the mass law of Seeger would reflect rigid constraints in the mass law formula which could result in larger deviations. Garvey et al. quote an average deviation of less than 0.2 MeV for their overall fit to the known masses. This deviation is about one-half the rms deviation of their mass law from the beta decay energies measured in this work. Seeger, however,

quotes an average deviation of 0.78 MeV to the known masses. The 0.63-MeV rms deviation of his mass formula from the values in this work is well within the deviation noticed by him for the known masses. Although no conclusive evidence can be given, this increase of the deviations for the nuclei in this study, using the mass relation of Garvey et al., could indicate onset of a breakdown for this relation in the regions far from beta stability. On the other hand, the predictions of Seeger, though less accurate, are still within his quoted deviation in the region of this study. On the basis of these comparisons, it appears that the mass relation of Garvey et al. would be used to advantage to predict decay energies for short-lived radioactive nuclei likely to be studied in the reasonable future, but that the mass formula of Seeger is perhaps uncontested (although untested directly) for use in the extreme neutron-rich region traversed in nucleogenesis calculations.

Way and Wood (8), in a systematic study of the beta decay energies, coupled the decay energies between nuclei of four groups; odd Z-odd N, odd Z-even N, ~~even~~ Z-odd N and even Z-even N. For nuclei within each of these groups, the semi-empirical mass formula predicts linear or almost linear dependence of the beta decay energy on N for Z=constant, A=constant or $I (=N-Z)=\text{constant}$. This linear behavior was tested by Way and Wood and it was discovered that the deviation from linearity is very pronounced in those regions near major shell closure. This behavior is expected since the mass formula used has no shell-model dependence. Examples of this deviation are shown in Figures 18 through 21 which show "Way-Wood" diagrams for the mass region around $A = 140$, for even-even, odd-odd, odd A-odd Z

Figure 18. Way-Wood diagram for even-A even-Z nuclei in the mass range around A=140

Figure 19. Way-Wood diagram for even- A , odd- Z nuclei in the mass range around $A=140$

Figure 20. Way-Wood diagram for odd-A odd-Z nuclei in the mass range around A=140

Figure 21. Way-Wood diagram for odd- A even- Z nuclei in the mass range around $A=140$

and odd A-even Z nuclei, respectively. These diagrams have been made showing the beta decay energy versus mass number, to conform to recent convention in the literature (2). Previously measured beta decay energies are indicated by open circles and the results of this work are indicated by open squares. Lines have been drawn connecting the points to indicate lines of constant Z and N. It may be noted that as the major shell at $N = 82$ is crossed, the line of constant Z shows a large discontinuity in slope. However, this slope change appears, from the figures, to be independent of Z, at least for neighboring lines. As an example, examine $N = 82$ in Figure 18. The slope between $N = 82$ and $N = 84$ for $Z = 62, 60, 58, 56,$ and 54 is 2.4, 2.4, 2.7, 2.8, and 2.8 MeV, respectively. The largest slope difference between adjacent lines of constant Z occurs between $Z = 60$ and $Z = 58$, and is equal to 0.3 MeV. This represents the largest deviation from parallel slopes found in all the nuclei shown in Figures 18 through 21. Most of the other deviations are 0.1 MeV or less. Thus, even though the linearity itself breaks down, lines of adjacent Z remain remarkably parallel and this behavior can be utilized to predict as yet unmeasured decay energies. The beta decay energies for ^{140}Xe , ^{141}Cs and ^{142}Cs were predicted, on the basis of these systematics, to be 4.3, 5.1, and 6.7 MeV respectively, representing an rms deviation of less than 0.2 MeV, compared to the results of this work.

Predicted beta decay energies are indicated by open triangles in the figures and are connected to known decay energies via dashed lines of constant Z and N. The beta decay energy for ^{144}Ba is predicted to be 3.2 MeV as shown in Figure 18. This prediction was made possible because

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The beta decay energies for ^{138}La and ^{144}La are predicted to be 7.5 MeV and

565 MeV respectively as shown in Figure 19. These predictions were made

possible because of the measurement of the beta decay energy for ^{138}Cs by

G. H. Carlson (51) and the measurement of the beta decay energy for ^{142}Cs

G. H. Carlson (51) and the measurement of the beta decay energy for ^{142}Cs

in this work. The beta decay energy for ^{143}Ba is predicted to be 4.0 MeV

as shown in Figure 21, and results from the measurement of the beta decay

energy of ^{141}Xe in this work. The uncertainty in these predictions is

likely to be no more than 0.3 MeV. This error represents a combination

likely to be no more than 0.3 MeV. This error represents a combination

of the deviation from parallel slopes and the accuracy with which the

method predicted beta decay energies measured in this work. Using the

predicted value for the beta decay energy of ^{138}I as a standard, the

value for the beta decay energy of ^{140}I is predicted to be 8.5 MeV, as².

shown in Figure 19. However, since the decay energy for ^{138}I is itself

a predicted value, and is used to predict another decay energy, it may

be expected that the uncertainty involved would increase to 0.4 MeV,

reflecting simple error propagation. The alpha decay, two-neutron separa-

tion and two-proton separation energies for these five nuclei are unknown

so the above predictions are based solely on the previously measured

beta decay energies in this region, and the characteristics of the Way-

Wood systematics.

[illegible]

B. ICC Determinations for Transitions in the Decay of ^{140}Xe

The ground-state configuration for ^{140}Cs is $(g_{7/2})^5$ for the protons

and $(f_{7/2})^2$ for the neutrons. According to the ground-state properties of

the neighboring nuclei, ^{137}Cs and ^{143}Ce , the five protons couple to spin $7/2^+$ and the three neutrons couple to $3/2^-$ (32). According to the ground-state spin coupling rule developed by Brennan and Bernstein (52), this proton-neutron configuration should result in a ground-state spin-parity of 2^- (53). Schick et al. (19) predict 1^+ for the spin-parity of the 1427-keV level of ^{140}Cs , based on the extremely strong beta feeding from the 0^+ even-even ^{140}Xe and the possible positive parity shell model states available at this excitation energy for this region of nuclei. The log ft value for this beta feeding is 4.47, which substantiates the 1^+ assignment. On the basis of these two spins and parities, the spins and parities for 14 levels in this decay scheme are predicted, using the ICC results for 18 transitions.

The 653-keV level de-excites via an E2 transition to the 2^- ground state which limits the spin of the level to 0, 1, 2, 3 or 4, all with odd parity. The log ft value of the beta branch to this level is 6.3, which is consistent with a first-forbidden transition having a spin change of 0 or ± 1 . This further limits the spin of the level to either 0 or 1 with odd parity.

The 622-keV level is connected via an E1 transition to the 1427-keV 1^+ level which limits the spin to 1 or 2, both with odd parity. However, this level is not beta fed which would indicate that the first forbidden non-unique beta transition is not possible, thereby eliminating spins less than 2. The spin assignment for this level is thus 2, with odd parity.

The 438-keV level de-excites via an M1 transition to the ground state

suggesting the spin of the level to be 1, 2 or 3 with odd parity. This level also is not beta fed which limits the spin choices to 2 or 3, with odd parity.

The 345-keV level is connected to the 622-keV level via an M1 transition, limiting the spin of the level to 1, 2, or 3, all with odd parity. However, the log ft value for the beta branch to the 345-keV level is 7.7, which would further suggest limiting the spin to either 0 or 1. Therefore, the level is assigned a spin-parity of 1^- .

The level at 294 keV is populated from the 622-keV level by means of an E2 transition allowing spin possibilities of 0, 1, 2, 3 or 4, all with odd parity. The log ft value for the beta branch feeding this level is 7.5, which further limits the deduced spin to 0 or 1, with odd parity.

The level at 212 keV has an E2 transition to the ground state, limiting the spin of the level to 0, 1, 2, 3 or 4, with odd parity. This level is only weakly fed from the 1427-keV level although the levels at 112 and 118 keV are strongly fed. This indicates that the spin must be at least 3 to preclude an E1 transition. It is unlikely that a spin as high as 4 would be seen through beta decay of an even-even nucleus, so the spin of the level is probably 3 with odd parity.

The level at 149 keV is connected to the 345-keV level via an E2 transition, limiting the spin of the level to 3 or less. Again, no feeding from the 1427-keV level suggests a spin greater than 2, making a plausible spin assignment of 3, with odd parity.

The 118.5-keV level is restricted to spin possibilities of 1, 2 or 3 from the presence of the M1 ground-state transition. This level is very strongly fed from the 1427-keV level which precludes a spin 3 possibility.

There is no beta feeding to this level which precludes the spin 1 possibility, leaving a unique spin assignment of 2 for this level, with odd parity.

The 112.5-keV level, like the 118.5-keV level, is strongly fed from the 1427-keV level and has no beta feeding, both conditions combining to limit the spin assignment to 2, consistent with the presence of an E2 ground-state transition.

The 103.0-keV level de-excites via an E2 ground-state transition, limiting the spin to 4 or less. The log ft value for the beta feeding to this level is 7.1, which further limits the spin to 0 or 1 with odd parity.

The M1 ground-state transition from the 80.1-keV level limits the spin of this level to 1, 2 or 3, with odd parity. The log ft value of 6.1 for the beta branch to this level indicates a first-forbidden beta transition with spin change no greater than 1. Therefore, the spin of this level is 1, with odd parity.

The M1 transition from the 294-keV level to the 64.6-keV level limits the spin of the latter level to 2 or less. The log ft value for the beta feeding to this level is 9.1, indicating a first-forbidden unique transition with spin change of 2 from the 0^+ ground state of ^{140}Xe . This limits the spin of the level to 2 with odd parity.

The 13.9-keV level is connected to the 64.6-keV level via an M1 transition, limiting the spin of the lower level to 1, 2 or 3 with odd parity. This level is also strongly fed from the 1427-keV level, which further limits the spin to 1 or 2, with odd parity.

The 232-keV level is connected to the 64.6-keV level via an M1 transition, limiting the spin of the level to 1, 2 or 3 with odd parity. This level, however, is not beta fed which precludes a possible spin less than 2.

Figure 22 shows the proposed decay scheme for the beta decay of ^{140}Xe where the arrows indicate beta-fed energy levels with the associated log ft values and percent beta feeding (in parentheses). According to the proton and neutron configurations, this decay scheme should resemble the decay scheme for ^{142}Cs since they both have the same proton number and the $(f_{7/2})^3$ neutron configuration for ^{140}Cs should show similar characteristics to the $(f_{7/2})^5$ configuration for ^{142}Cs . The level scheme for ^{142}Cs has been determined by Larsen et al. (50) and a cursive examination of the level scheme indeed points up some similarities. Both level schemes show a preponderance of low-energy levels although the number for the level scheme of ^{140}Cs is higher than that for ^{142}Cs (11 under 500 keV as opposed to 8). The beta decay energy for ^{142}Xe is about 1 MeV higher than that for ^{140}Xe , as is expected since the former is two more neutrons removed from beta stability. Also, the 1312-keV level in ^{142}Cs is strongly beta fed, and could be the analog to the 1427-keV state in ^{140}Cs .

Roy and Nigam (54) calculate possible total spins for a $(7/2)^3$ configuration to be 3/2, 5/2, 7/2, 9/2, 11/2, and 15/2. Assuming the ground-state configuration of five $g_{7/2}$ protons coupled to 7/2 and three $f_{7/2}$ neutrons coupled to 3/2, it is possible to combine these spins to form states having total angular momenta of 2, 3, 4 or 5. Assuming the neutrons would then couple to spin 7/2, the protons would combine to form states with

Figure 22 (Continued). High-energy part of ^{140}Cs level scheme. Starred gamma rays are used twice. 4.47 (71.0) denotes log ft (percent beta feeding)

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Table 11. Energy levels in ^{140}Cs

Energy Level	Proposed Configurations	J^π
0	$[\pi(g_{7/2})^5_{7/2} \nu(f_{7/2})^3_{3/2}]_2$	2^-
13.9	$[\pi(g_{7/2})^5_{3/2} \nu(f_{7/2})^3_{3/2}]_1$	1^-
64.6	$[\pi(g_{7/2})^5_{3/2} \nu(f_{7/2})^3_{7/2}]_2$	2^-
80.1	$[\pi(g_{7/2})^5_{7/2} \nu(f_{7/2})^3_{7/2}]_1$	1^-
103.0	$[\pi(g_{7/2})^5_{3/2} \nu(f_{7/2})^3_{3/2}]_0$	0^-
112.5	$[\pi(g_{7/2})^5_{3/2} \nu(f_{7/2})^3_{3/2}]_2$	2^-
118.5	$[\pi(g_{7/2})^5_{7/2} \nu(f_{7/2})^3_{7/2}]_2$	2^-
149.0	$[\pi(g_{7/2})^5_{7/2} \nu(f_{7/2})^3_{3/2}]_3$	3^-
212.0	$[\pi(g_{7/2})^5_{3/2} \nu(f_{7/2})^3_{7/2}]_3$	3^-
232.0	$[\pi(g_{7/2})^5_{3/2} \nu(f_{7/2})^3_{3/2}]_3$	3^-
294.0	$[\pi(g_{7/2})^5_{7/2} \nu(f_{7/2})^3_{7/2}]_0$	0^-

facility, the beta decay energies measured in this work could be determined much more precisely. Plans are also being considered for the placing of the fissioning sample in the ion source thus shortening greatly the transport time and making possible the study of nuclei even further removed from beta stability. This, plus the possibility of different sample-ion source combinations to enhance the availability of fission products other than Xe and Kr would greatly facilitate the further systematic study of beta decay energies of the neutron rich nuclei produced in fission.

The internal conversion electron study for the decay of ^{140}Xe illustrates the value of such measurements and points up the need to continue such studies on odd-odd nuclei in this region. The present system, for example, could be utilized for the internal conversion electron study for the decay of ^{142}Xe , presently available at TRISTAN. Since this work, a new experimental system has been developed to study internal conversion electrons. This system uses a beta-gamma, beta-conversion electron dual coincidence technique to reduce the beta continuum to improve the accuracy of the conversion electron intensity measurements, and make possible the identification and study of weakly converted transitions.

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VII. APPENDICES

A. The Two-Absorber Method for Correction of Scintillation Spectra for Gamma-Ray Contributions

One means of correcting scintillation spectra for the effects of gamma-ray detection involves a "two absorber" method, where three spectra are combined to obtain the true beta spectrum. The first spectrum is obtained using no absorber between the MTC and the plastic scintillator. The second spectrum is obtained using an absorber whose thickness is greater than the range of the most energetic electrons in the spectrum. The third spectrum is obtained using the next larger absorber.

The basic assumptions used in the procedure to obtain the true beta spectrum are: (1) the source activity is constant during the three measurements, and (2) the absorption of gamma rays in the absorbers is proportional to the thickness of the absorber used (i.e. one can approximate the absorption of gamma rays by a straight line over the range of thicknesses used). The first assumption limits the useful application of this technique to singles spectra, since this assumption can break down during the inherently long time duration of a coincidence experiment. Figure 23 illustrates the basis for this correction technique, where the indicated quantities are defined as follows:

- G_0 the intensity of a photon of arbitrary energy at the detector with no absorber in place;
- G_1 the intensity of a photon of arbitrary energy at the detector with an absorber of thickness X_1 in place;
- and

Figure 23. Exponential absorption curve and linear approximation for gamma rays through an absorber

G_2 the intensity of a photon of arbitrary energy at the detector with an absorber of thickness X_2 in place.

Thus, using the straight line approximation to the absorption curve,

$$(G_0 - G_1)/X_1 = (G_0 - G_2)/X_2$$

or

$$G_0 = (X_2 G_1 - X_1 G_2)/(X_2 - X_1) .$$

If X_1 is large enough to stop all electrons in the beta spectrum, G_1 can be measured directly by counting the spectrum with the absorber in place for a fixed amount of time. If $X_2 \geq X_1$, G_2 can be similarly measured. Therefore, the photon spectrum in the plastic scintillator in a given time t is given by

$$G_0(t) = (X_2 G_1(t) - X_1 G_2(t))/(X_2 - X_1) .$$

This spectrum is then subtracted from that obtained with no absorber to yield a true beta spectrum.

It should be noted that the break-down of the basic assumption of a linear absorption curve will be greatest for the low-energy photons. However, since the interest in the final beta spectrum is in the high-energy end of this spectrum, it is this portion of the spectrum that must be corrected most nearly completely. The linear absorption curve assumption is good for photons giving responses in this energy region. The magnitude of this correction is small, with a ratio of the number of photon-caused events in the plastic scintillator to the electrons counted by the detector ranging from 1% to 15% in the energy region most critical to the measurement of the end-point energy. As an example, for the

singles measurement of ^{141}Cs , the photon-caused events comprise less than 10% of the spectrum for energies within one MeV of the end-point energy.

B. The One-Absorber Method for Correction of Scintillation Spectra for Gamma-Ray Contributions

The count rate for coincidence measurements is proportional to the product of the solid angles and efficiencies of the detectors. Since these factors for the Ge(Li) gamma detector are small, the coincidence counting rate is much lower than the corresponding singles counting rate. As was mentioned in Appendix A, the activity for the three counting periods used for the two-absorber correction technique is assumed to be constant. During the inherently longer counting periods involved with a coincidence experiment, this assumption is subject to question. Therefore, a different method was used to correct for the Compton response of the plastic scintillator, in coincidence measurements, which is described below. This method uses the basic assumption that the beta absorbers used result in negligible attenuation of gamma-ray intensities. For such a case, if a given number of coincidences (say, the number required to fill the coincidence event buffer memory) consists of B beta-gamma events and G_1 gamma-gamma events obtained with no absorber in a time T_1 , then, with an absorber in place, the same number of coincidences, G_2 , taken in the time T_2 , consists entirely of gamma-gamma coincidences. Since the absorber has screened the detector from the electrons, the time T_2 will in all cases be longer than T_1 . G_1 can be found from G_2 by the relation

$$G_1 = G_2(T_1/T_2).$$

T_1 and T_2 can be determined from a relatively short-duration (and hence

more nearly constant activity) experiment. Subsequent data can then be taken for absorber-to-no absorber coincidence count ratios of $n_2/n_1 = T_1/T_2$. In other words, n_1 buffers of data taken without an absorber minus n_2 buffers taken with an absorber to block out all electrons will yield data that contains only beta-gamma coincidence events, or mathematically,

$$n_1(B + G_1) - n_2G_2 = n_1B_1 + (n_1G_1 - n_2G_2) = n_1B.$$

This derivation breaks down to the extent that gamma rays are attenuated by the absorber. However, the breakdown is most pronounced for low-energy photons, and the effect on the high-energy portion of the spectrum, used to determine the beta decay energy, is small.

C. Computer Programs Used for Data Analysis

Computer programs used were as follows:

CARD

CARD is a Fortran program which is basically a plotting routine. It can be used to correct, compress and punch the data onto cards to be used as input for other programs. In this experiment, all beta-gamma coincidence, beta singles and plastic scintillator calibration data were treated first with this program. Integral compression factors were specified to reduce the data range to 128 channels. Dropped channels or low-energy channels having data register overflows were corrected before the plotting and punching procedures.

CALIB

CALIB is a CPS/PL-1 language program used to determine the plastic

scintillator energy calibration. The program uses as input the appropriate channel and energy information from the several activities used to calibrate the plastic scintillator. It then performs a fit to the data of a calibration curve having the functional form:

$$E = SN + D \quad N \geq N'$$

$$SN + D \left[1 - \frac{(N' - N)^2}{N'} \right] \quad N \leq N'$$

Where N' is the cross-over channel, representing the transition point from linear to quadratic energy dependence, S is the slope of the linear part of the calibration curve and D is the intercept of the linear part of the calibration curve.

This program performs a least-squares fit to the data while holding the cross-over location constant. It then increments the cross-over and recalculates the slope and intercept, stopping when a minimum value for the weighted sum of the square of the deviations is reached.

ISOBAR

ISOBAR is a CPS/PL-1 program which used the solution of the Bateman equations to predict activities present for the nuclei studied with the TRISTAN system (55). The physical parameters of the MTC operation are part of the program as are the half-lives for the various decay chains studied with the isotope separator. The output includes the integrated activity ratio for each member of the decay chain as a function of MTC mode and time parameters.

FERMI

FERMI is a Fortran program written for the analysis of continuous

beta spectra. It integrates the theoretical true spectrum over the response of the plastic scintillator to fit the measured spectrum in a linear, iterative, least square manner. This technique avoids the problems normally encountered with the common unfolding techniques which unfold the measured spectrum over the response of the detector to find the true spectrum. As such, it is of great value for the fitting of beta spectra with poor statistics where iterative unfolding techniques are unstable. It is basically a two parameter fitting routine which allows only one amplitude and one end-point energy to vary. However, with accurate knowledge of the relative beta feeding to the various levels in the daughter nucleus together with accurate knowledge of the energy level differences, it can be used to fit up to 5 individual beta groups in a complex spectrum.

Figures 24 through 26 illustrate the ability of this program to fit both simple and complex beta spectra. Figure 24 shows the FERMI output for the beta spectrum following the decay of ^{144}Pr . It is a simple spectrum containing only one group, the ground-state to ground-state decay from ^{144}Pr to ^{144}Nd . Figure 25 shows the FERMI output for the beta decay of ^{137}Xe , which was fit assuming two groups: 1) decay to the ground state (70%); and 2) decay to the 0.456-MeV level in ^{137}Cs (30%). Figure 26 shows the FERMI output of ^{88}Rb . This was fit using three groups including beta feeding from ^{88}Rb to the ground state (81%), the level at 1.830 MeV (4%) and the level at 2.73 MeV (15%). The ground-state feeding is assumed to have a first-forbidden unique shape as evidenced by the non-linear Kurie plot.

Figure 24. Measured spectrum and Kurie plot for ^{144}Pr calibration source showing the FERMI fit to each

Figure 25. Measured spectrum and Kurie plot for ^{137}Xe calibration source showing the FERMI fit to each

Figure 26. Measured spectrum and Kurie plot for ^{88}Rb calibration source showing the FERMI fit to each

In addition to its value as a fitting routine, FERMI can be used to determine the true spectrum by an iterative unfolding technique. Since the iterative unfolding technique is sensitive to statistical fluctuations in the data, smoothing can be specified between each iteration. The fitting procedure has been reported elsewhere (56). The following relations briefly describe the unfolding procedure: If $D(E)$ is the input data, $T_n(E)$ is the "true" spectrum, $M_n(E)$ is the distorted "true" spectrum, $R(E, E')$ is the response of the detector, and n is the iteration number, then,

$$M_n(E) = \int T_n(E') R(E, E') dE' .$$

In the absence of additional information, the input data are taken as the first approximation to the true spectrum, or, $T_0(E) = D(E)$. Subsequent iterations use the difference between the input data $D(E)$ and the distorted true spectrum, $M(E)$ for the n th iteration, or

$$T_n(E) = T_{n-1}(E) + (D(E) - M_{n-1}(E)) .$$

The iterations cease when a least square condition is reached or when a maximum number of iterations is reached.

SPEC

SPEC is a Fortran program used to fit undistorted beta spectra. Since the effects of the response of the detector have already been removed from the data, the fitting is linear, provided the shape factor is statistical. The program can fit up to 19 groups simultaneously in either a FERMI stripping or a least-squared manner. In this procedure, the

end-point energies and amplitudes of each group can be allowed to vary freely. Figure 13 shows the fit from SPEC to the spectrum in coincidence with the 0.360-MeV gamma transition following the decay of ^{142}Cs . This fit shows the four groups comprising the complex beta spectrum. Figure 12 shows similar plots for the beta singles spectrum in the decay of ^{141}Cs . Four groups were also found in this spectrum.

CALQ

CALQ is a CPS/PL-1 program written for the purpose of calculating the weighted average of the beta decay energy from all the gated spectra for a given beta decay. The program finds a weighted average of the decay energies using the reciprocal of the square of the uncertainty as the weight. The uncertainty of the final result is the weighted rms deviation of the different end-point energies.

PEAKFIND & SKEWGAUS

Both of these programs are Fortran programs written for the purpose of fitting skewed Gaussian peaks in gamma-ray and conversion electron spectra (24). The following functional form is assumed for the shape of the peaks:

$$F(X) = N_0 (e^{-X_0(2X-X_0)} (1-A + B(X-X_0)^{N_b}) + A) \quad X \leq X_0$$

$$N_0 (e^{-X^2} (1-A) + A) \quad X_0 \leq X \leq 0$$

$$N_0 e^{-X^2} (1 + C(-X)^{N_c}) \quad X \geq 0$$

where N_0 is the height of the peak, X_0 is the cross-over channel, X is

the signed channel difference from the centroid, A is the backscatter tail parameter, B is the lower skewness parameter, C is the upper skewness parameter, N_b is the lower skewness power, and N_c is the upper skewness power. Both programs use a matrix inversion, least square fitting procedure. PEAKFIND scans the entire spectrum, finds the peaks and fits them with N_0 , X_0 and σ (the Gaussian width) as possible free parameters. SKEWGAUSS fits individual peaks and/or multiplets and allows N_0 , X_0 , σ , A , B , C and the centroid to vary for any member of the multiplet. In addition, any of the free parameters may be fixed relative to one of the peaks in the multiplet. This latter option is especially useful if the peaks in the multiplet are either poorly resolved or if one peak is much smaller than another.

LOG FT

LOG FT is an extension of a subroutine found in FERMI. It uses the half-life and beta decay energy of a nucleus together with the energies and percent beta feeding for the levels in the daughter nucleus to calculate the Fermi integral and the comparative half-life, or log ft value for the beta decay to energy levels in the daughter nucleus.