On-Line Studies of Mass-Separated Xenon Fission Products

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Mass-separated, short-lived Xe fission products from Cf^{252} have been studied using on-line nuclear spectroscopy. The Xe isotopes from a 10-μg Cf source were separated in the Princeton Isotope Separator, and the decay properties of the separated isotopes were measured with a Ge(Li) detector located at the collector of the separator. Results from measurements of the decay of $Xe^{137-142}$ and accompanying Cs and Ba isotopes are discussed.

INTRODUCTION

EVER since the discovery of the fission process, considerable interest has centered on studies of the nuclear properties of the fission-product nuclei and the decay sequences through which these species transform to other nuclei lying closer to the region of nuclear stability. Such studies have often employed fast chemical procedures or physical-separation techniques to achieve a partial separation of the complex mixture of fission products. Nevertheless, detailed studies of the shortest-lived fission products have usually been fragmentary because of the inability to study any one isotope without the interfering radiations from others. The latter may be formed simultaneously with the species of interest during the fission process or may arise as radioactive daughters following decay of the isotopes originally separated.

With the development of laboratory-scale isotope separators, it has become possible to attempt simultaneous mass-separation and study of fission products using "on-line" techniques whereby fission products are continuously formed, separated, and examined using nuclear spectrometers. The first such study carried out was that of Kofoed-Hansen and Nielsen,[1] who swept gaseous fission products from the cyclotron of the Bohr Institute to an isotope separator. This procedure permitted the investigation of the half-lives of several short-lived inert-gas fission products. The detailed analysis of the complex radiations accompanying the decay of these isotopes has had to await the recent introduction of semiconductor spectrometers and large multichannel analyzers.

Recently, spectroscopic programs for the on-line study of mass-separated fission products have commenced at the Nobel Institute for Physics, Stockholm,[2] and the Ames Laboratory, Iowa,[3] using a cyclotron and reactor, respectively, to produce the fission products.

The spontaneous fission of Cf-252 affords another source of fission products for study and offers several advantages. First, there is no high-level background radiation due to accelerator or reactor operation that requires shielding. Second, the compact source may be mounted very close to the ion source of the separator, so that holdup time is kept to a minimum. Finally, the small container of Cf and a small cylinder of sweeping gas can be maintained at the 50–60-kV accelerating potential of the isotope separator. In this way, potential gradients causing glow discharge in gas lines leading to the ion source of the separator are avoided.

Californium-252 has a reported half-life of 2.55 years; the decay of this isotope proceeds by a 3% spontaneous-fission branch, with the rest of the decay occurring by α emission. If a source of 10 μg of Cf-252 is available, and if a fission product produced with a fission yield of 1% can be mass-dispersed through the isotope separator with an efficiency of 10%, then a steady-state rate of 6×10^3 disintegrations/sec may be anticipated at the collector. This activity level is sufficient to attempt spectroscopic investigation using Ge(Li) semiconductor spectrometers.

We report here the results of an investigation into the over-all feasibility of this on-line technique and some data obtained on the decay of various Xe and Cs isotopes produced in the spontaneous fission of Cf-252. The results of preliminary investigations by us into the feasibility of this technique have been given elsewhere.[4]

EXPERIMENTAL TECHNIQUE

Production and Separation of Isotopes

Sources of up to 12.8 μg of Cf-252 were obtained on loan from the Research and Development Division of the U. S. Atomic Energy Commission. The actual preparation of the sources was done by the Chemistry Division of the Lawrence Radiation Laboratory at Berkeley. The Cf was deposited on a thick platinum backing and covered with a replaceable nickel foil to impede the self-transfer of the Cf to the surroundings. It was found that a cover foil of about 400 μg/cm^2 was sufficient to keep the self-transfer at a manageable rate without significantly affecting the escape of fission fragments from the source.

[1] O. Kofoed-Hansen and K. O. Nielsen, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. **26**, No. 7 (1951).
[2] S. Borg, U. Fägergvist, G. Holm, and F. Kropff, Nucl. Instr. Methods **38**, 295 (1965).
[3] W. L. Talbert, Jr., and D. Thomas, Nucl. Instr. Methods **38**, 306 (1965).
[4] G. Sidenius, R. M. Gammon, R. A. Naumann, and T. D. Thomas, Nucl. Instr. Methods **38**, 299 (1965).

In air, the cover foils deteriorate rapidly, apparently because of the formation of corrosive nitric oxides due to passage of fission fragments through the air. Although in vacuum or in an atmosphere of an inert gas there is considerably less damage, it was necessary to change the cover foils every few months. With each foil change there was a significant loss of Cf that had transferred to the cover foils. As a result, the total amount of Cf available decreased markedly during the course of this experiment.

The use of emanation techniques for studies of radioactive isotopes of the rare gases is at least 40 years old. A review of the technique has been made by Wahl.[5a] After some preliminary investigations, barium stearate was chosen as emanator. This material has been used extensively by Wahl[5b] in studies of the independent yields of Xe and Kr isotopes produced in fission.

A schematic drawing showing the mounting of the Cf source relative to the emanator is shown in Fig. 1. Fission products leaving the source were stopped in the barium stearate from which the rare-gas fission products diffused rapidly. Stable Xe was passed over the emanator and was fed together with the radioactive isotopes into the ion source of the Princeton electromagnetic isotope separator (a 90°-sector machine). The stable Xe provided a support gas for the ion source and measurable ion beams at the collector with which the mass positions could be determined and stabilized. The beam corresponding to the mass number of interest was passed through a collimator and down a 3-ft beam pipe to the detector box. All other beams were stopped at the normal collector position.

Detector Box

A schematic drawing of the detector box is shown in Fig. 2. This is the same apparatus described by Sidenius *et al.*[4] Either Ge(Li) or NaI(Tl) γ-ray detectors or plastic-electron detectors were placed at positions I, II, and III, and in some experiments a NaI(Tl) detector was placed above position I for coincidence measurements.

The beam was stopped at position I on a piece of moving aluminized-mylar tape. It was found that tape

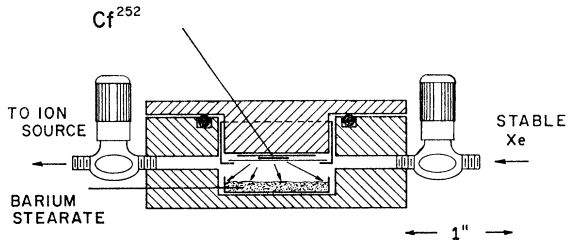


FIG. 1. Schematic drawing of californium-source assembly.

[5] (a) A. C. Wahl, in *Radioactivity Applied to Chemistry*, edited by A. C. Wahl and N. A. Bonner (John Wiley & Sons, Inc., New York, 1951), p. 284; (b) A. C. Wahl, R. L. Ferguson, D. R. Nethaway, D. E. Troutner, and K. Wolfsberg, Phys. Rev. **126**, 1112 (1962).

without a conductive coating became sufficiently charged to deflect the beam. The tape could be used to transport the radioactive atoms away from the vicinity of detector I and downstream to positions II or III, after the Xe isotope had decayed but before an appreciable amount of the Cs daughter had decayed. By noting the relative intensity of the various lines in a γ-ray spectrum at position I for different tape speeds, it is possible to assign these lines to Xe, Cs, or other isotopes occurring further along the decay chain. In Fig. 3 are shown the results of some calculations of relative counting rate at position I as a function of tape speed for the mass-140 and mass-142 decay chains. Note that high speeds are not necessary to strongly diminish the secondary products. In particular, we note that even though Xe-142 and Cs-142 have quite similar half-lives, it is still possible to produce a significant variation in these relative counting rates at a moderate tape speed.

In the actual experiments, the discriminations achieved between parent and daughter were somewhat less than those calculated above. This is attributable to incomplete shielding between positions I and II and some off-tape deposition of Xe.

The tape could also be run at such a speed that the predominant activity at position II was the Cs daughter. It was thus possible to record a Cs spectrum substantially free from the Xe precursor, and therefore to verify the data obtained at position I.

Detector System

The principal detector used in these experiments was a Ge(Li) detector of the planar type, with an area of approximately 4 cm^2 and a depletion depth of 6–7 mm. The combination of a Tennelec TC-130 preamplifier operated at room temperature and a Tennelec TC-200 main amplifier was used to achieve a resolution of 3.0 keV at an energy of 0.662 MeV and 4.0 keV at 1.332 MeV. Pulse-height analysis was made in 2048 channels of a Nuclear Data ND-161 pulse-height analyzer equipped with digital-gain stabilization. This last feature proved essential, since some measurements spanned periods up to 4 days. No loss in resolution occurred during these runs. Typical counting rates were 10–20 thousand counts/min at mass 140, compared to a background of about 100 counts/min. At mass-142, the counting rates dropped to about 1200 counts/min; at mass-144, the counting rate was only slightly above background, and attempts to accumulate spectra were unsuccessful.

Energies of observed γ lines were determined by use of standard sources. The standard lines were not accumulated simultaneously with the actual measurements of unknowns, but immediately before and after. Digital stabilization on a mercury-pulser peak was maintained during the collection of both standard and unknown spectra. Care was taken to see that counting

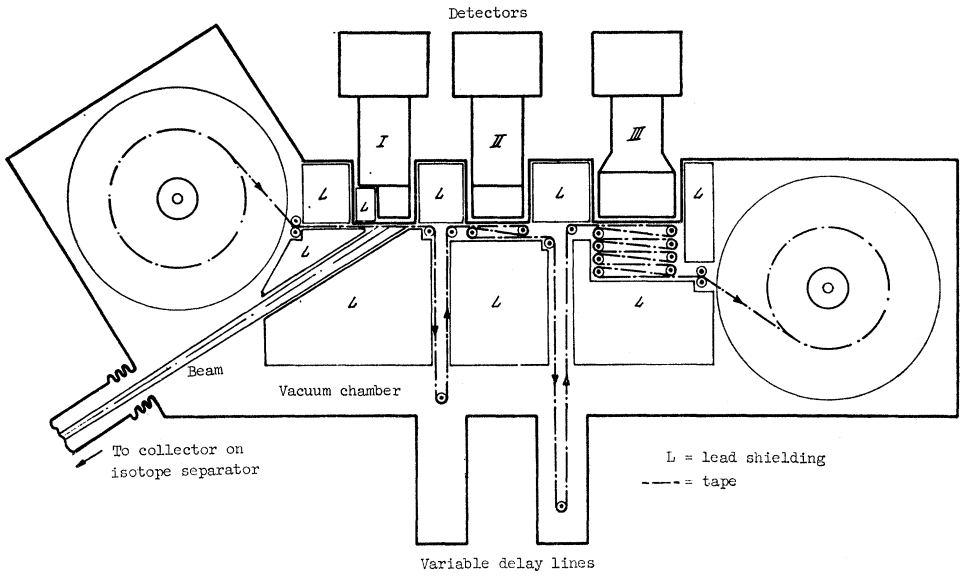


FIG. 2. Schematic drawing of detector box with moving-tape assembly.

rates were kept low so as not to incur gain shifts associated with excessive repetition rates. Annihilation quanta resulting from pair production by high-energy γ rays in the surrounding lead shielding provided an internal check on the energy calibration. A computer program was used to locate peak positions of both standard and unknown lines, and the positions of the standard lines were least-squares-fitted to an energy expression that was quadratic in the channel number. This calibration technique plus the reproducibility of energies from spectrum to spectrum under different experimental conditions allowed the determination of most energies to a precision of 1 keV or less.

In order to extract relative-intensity information from the spectra, we measured the efficiency of the detector as a function of γ-ray energy. This was accomplished with a set of standard sources purchased from the International Atomic Energy Agency. The disintegration rates of these sources had been determined by the IAEA to an accuracy of 2–3%.

NaI(Tl) γ-ray spectrometers coupled to conventional electronics were used to examine the very-high- and very-low-energy ends of the γ-ray spectra, where the efficiency of the Ge(Li) detector is small.

The high-energy regions of the β spectra were studied with a plastic scintillator (cylindrical shape, diam=2 in., depth=2 in.). The detector was calibrated with K-42 and Cl-38, which have reported β end-point energies of 3.5 and 4.8 MeV, respectively.

TABLE I. Half-lives determined in this work.

Isotope	Half-life (sec)
Xe^{139}	39.3±0.7
Xe^{140}	14.3±1.3
Xe^{141}	1.8±0.2
Cs^{140}	65.7±1.6

Some half-life measurements were made using a multichannel analyzer as a multiscaler. Xenon was collected at position I for an appropriate length of time. Then the beam was stopped and the multiscaler simultaneously started. The number of events detected in successive equal-time intervals was stored in successive channels of the analyzer. In some cases, this procedure was repeated 10 or 20 times to accumulate enough events for a meaningful analysis. The data were analyzed by least-squares methods to give the half-lives.

RESULTS

Half-Life Measurements

The half-lives determined in these experiments are given in Table I. Only one determination was made for Xe-139 and -141. The half-life values and errors are

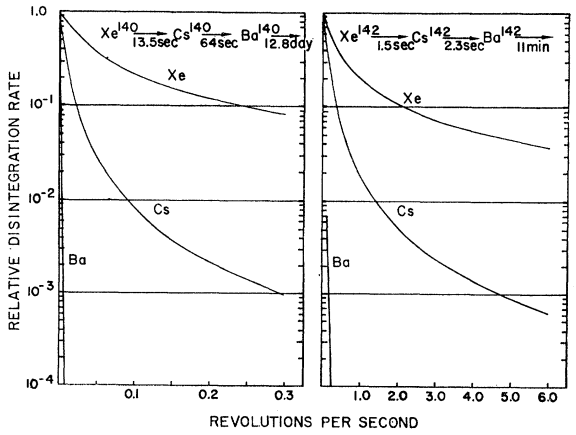


FIG. 3. Calculated relative counting rate at detector position I (see Fig. 2) as a function of tape speed for the mass-140 and mass-142 decay chains. One revolution corresponds to 4 cm.

TABLE II. β end-point energies determined in this work.

Isotope	End-point energy (MeV)
Xe^{140}	4.7±0.5
Cs^{140}	6.2±0.6
Cs^{142}	7.6±0.8

those determined from a least-squares fit to the decay curves. Four measurements were made for the mass-140 isobars—two designed to optimize determination of the half-life of Cs-140 and two designed to optimize the determination of that of Xe-140. The values shown are statistically weighted averages. The errors are the root-mean-square deviations from the weighted average and are also statistically weighted. The half-lives presented in Table I are in agreement with other recent results.[6]

β-Ray Measurements

By comparing the results from measurements with moving and stationary tape, it was possible to estimate the β end-point energies in the decay of Xe-140 and Cs-140. For mass number 142, only the β end-point energy in the decay of Cs-142 could be determined because of the similar half-lives of Xe-142 and Cs-142. No effort was made to analyze the β spectra in detail to obtain different branches. The measured β end-point energies are given in Table II.

For the decay of Cs-140, Zherebin *et al.*[14] have found that an intense β branch goes to the first excited 2^+ level in Ba-140, but no β branch to the ground state has been observed. The same is true for the decay of Cs-138.[13] Assuming that Cs-142 decays in a similar way as Cs-138 and -140, i.e., that the measured β end-point energy corresponds to a decay to the first excited 2^+ level in Cs-142, the total decay energy of this isotope may be estimated to be 7.9±0.8 MeV. The corresponding energy for Cs-140 is found to be 6.8±0.6 MeV. These decay energies may be compared with estimates obtained from recent semiempirical mass formulas. For instance, the decay energies for Cs-140 and -142 obtained from Myers and Swiatecki's[7] mass formula are 6.6 and 7.5 MeV, from Garvey and Kelson's[8] mass

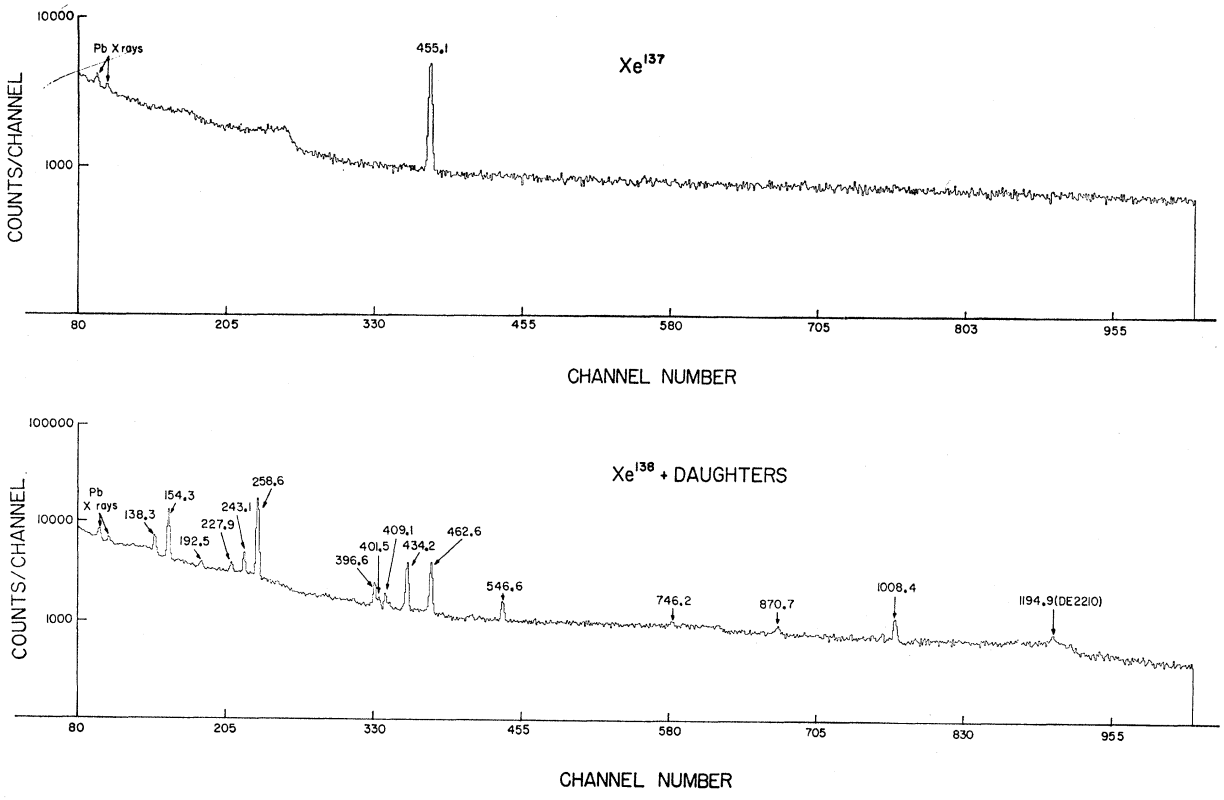


FIG. 4. Upper curve, γ radiation observed from mass-137 decay chain; lower curve, γ radiation observed from mass-138 decay chain.

[6] P. Patzelt and G. Herrmann, in *Proceedings of the Symposium on Physics and Chemistry of Fission, Salzburg, 1965* (International Atomic Energy Agency, Vienna, 1965), Vol. II, p. 245.
[7] W. D. Myers and W. J. Swiatecki, University of California Radiation Laboratory Report No. 11980, 1965 (unpublished).
[8] G. T. Garvey and I. Kelson (private communication).

TABLE III. Energies and relative intensities of observed γ transitions.[a]

Parent	E	I^a	E	I^a
Xe^{137}	455.1±0.5			
Xe^{138}, Cs^{138}	138.3±1.5	3.7	409.1±1.5	10.4
	154.3+1.5	15.0	434.2±1.5	60.5
	192.5±1.5	2.0	462.6±1.5	67.0
	227.9±1.5	4.4	546.6±1.5	21.4
	243.1±1.5	9.6	746.2±1.5	8.0
	258.6±1.5	100	870.7±1.5	17.1
	396.6±1.5	20.0	1008.4±2.0	52.7
	401.5±1.5	7.5	1194.9±2.0[b]	
Xe^{139}, Cs^{139}, Ba^{139}	101.6±2.0	0.4	491.5±1.5	3.2
	120.2±2.0	0.9	514.5±1.5	4.6
	165.7±1.5	8.6	612.6±1.5	9.4
	175.0±1.5	33.4	626.6±1.5	5.0
	218.8±1.0	100	724.0±1.5	2.4
	225.6±1.5	4.5	732.4±1.5	3.1
	289.9±1.5	18.7	788.3±1.5	5.3
	296.6±1.5	42.2	1107.4±2.0	13.6
	393.5±1.5	14.4	1284.0±2.0	8.8
Xe^{140}	47.3±2.0	5.2	445.1±1.0	4.2
	79.4±2.0	22.4	454.5±1.5	<0.5
	87.7±2.0	1.9	461.7±0.5	9.7
	92.5±2.0	<1	503.3±0.5	2.0
	103.0±1.0	11.7	514.8±1.0	5.7
	111.6±1.0	18.3	518.9±1.0	6.2
	117.5±1.0	21.6	547.8±0.5	6.6
	158.6±1.5	0.4	557.2±0.3	28.7
	163.6±1.5	1.4	608.1±1.0	13.8
	166.7±1.5	5.9	622.0±0.3	40.3
	182.0±1.5	1.3	627.4±1.0	3.9
	197.6±1.0	4.9	638.9±0.5	7.3
	202.6±1.5	0.8	646.1±1.5	0.8
	212.2±1.0	14.4	653.4±0.3	31.4
	258.4±1.5	1.2	773.9±0.3	21.3
	277.4±1.0	4.2	805.4±0.3	100
	281.2±0.5	10.7	879.5±0.5	11.6
	290.7±0.5	3.4	951.3±1.0	3.0
	331.2±0.5	2.0	988.9±1.0	16.2
	373.9±0.5	4.0	1136.5±1.0	7.8
	390.1±0.5	9.2	1207.4±1.0	5.5
	396.5±0.5	4.7	1308.8±1.0[c]	30
	411.6±1.5	<0.5	1314.6±1.0	34.1
	429.4±0.5	4.0	1413.1±1.0	51.2
	438.6±0.5	19.2	1426.0±2.0	3.7
Cs^{140}	528.2±0.5	5.8	1499.9±1.0	6.1
	602.2±0.3	100	1633.8±1.5	3.4
	671.9±1.0	2.4	1827.0±2.0	2.5
	735.5±1.0	1.0	1852.6±0.5	8.1
	830.7±0.5 (DE1853)		1948.2±1.5	2.0
	908.2±0.5	16.0	2031.0±1.5 (DE3055)	
	925.0±0.5 (DE1948)		2099.0±2.0	4.7
	1008.5±1.0	2.0	2237.4±2.0	3.1
	1079.5±1.0 (DE2099)		2329.6±2.0	3.6
	1130.3±1.0	5.5	2348.4±2.0[d]	
	1200.0±1.0	6.7	2429.4±2.0	4.6
	1215.5±1.0 (DE2238)		2522.4±2.0	5.0
	1221.2±1.0	4.2	2580.8±2.0[d]	
	1246.2±1.0	1.2	2772.7±2.0 (DE3794)	
	1308.8±1.0 (DE2330)		2924.3±2.0[d]	
	1390.8±1.0	2.4	3055.1±2.0	
	1408.2±1.5 (DE2429)		3794.0±2.0	
Ba^{140}, La^{140}	537.5±1.0			
	1594.9±2.0			
Xe^{141}, Cs^{141}, Ba^{141}, La^{141}	69.4±2.0	10.9	277.2±1.5	49.0
	74.6±2.0	3.9	304.7±1.5	55.1
	81.8±2.0	6.7	344.3±1.5	28.1
	89.7±2.0	2.3	460[e]	34.1
	100.9±1.5	6.4	468.2±1.5	17.8
	106.1±1.5	17.0	557.2±1.5	33.1
	113.4±1.5	2.5	589.6±1.5	14.4
	118.7±1.5	27.7	647.7±1.5	21.1
	137.7±1.5	1.4	910.4±1.5	41.6
	190.4±1.5	100		

TABLE III (*continued*).

Parent	E	I^a	E	I^a
Xe^{142}	92.1±2.0	1.4	395.1±1.5	22.9
	117.9±1.5	5.2	415.5±1.5	36.6
	123.8±1.5	4.7	538.7±1.0	82.8
	156.3±1.5	12.5	571.9±1.0	100
	163.5±1.5	12.9	618.0±1.0[f]	60
	191.6±1.5	26.3	644.7±1.0	59.9
	204.4±1.5	68.6	657.1±1.0	65.8
	212.6±1.5	5.3	736.7±1.0	5
	218.5±1.5	5.5	966.0±1.0	107
	252.3±1.5	2.6	1325.0±1.0	110
Cs^{142}	361.0±1.0			
Ba^{142}, La^{142}	74.3±2.0[g]		894.2±1.5	38.9
	121.2±2.0	<1	948.2±1.5	21.4
	176.6±1.5	1.9	999.6±1.5	13.1
	231.4±1.5	21.6	1077.5±2.0	19.5
	255.5±1.5	46.5	1202.7±2.0	34.4
	308.7±1.5	7.3	1375.1±2.0(DE2397)	
	424.8±1.5	11.0	1520.7±2.0	15.2
	433.4±1.5	2.4	2397.4±2.0	9.2
	641.6±1.5	100		
Mass 142 unassigned	198.4±2.0			
	241.5±2.0			
	335.3±2.0			
	600.9±2.0			
	1900.8±2.0			

[a] Energies are expressed in keV. Errors for relative intensities greater than 50 are to be taken as 15%; for those between 10 and 50, as 20%; for those less than 10, as 50%.
[b] This may be a double-escape peak for a previously reported 2210-keV transition.
[c] Even with moving tape, there is some contribution to the intensity of this line from DE2330, and an error of 30% in the relative intensity is therefore assigned.
[d] Since no double-escape peak is observed for this transition, it may be itself a double escape for an unobserved transition 1022 keV higher.
[e] This peak is quite broad and represents an unresolved doublet.
[f] Moving tape indicates a partial contribution to the intensity of this transition from a longer-lived daughter, and an error of 30% should be assigned to the relative intensity.
[g] This line is only partially resolved from lead K_α x rays, and no estimate of its relative intensity was possible.

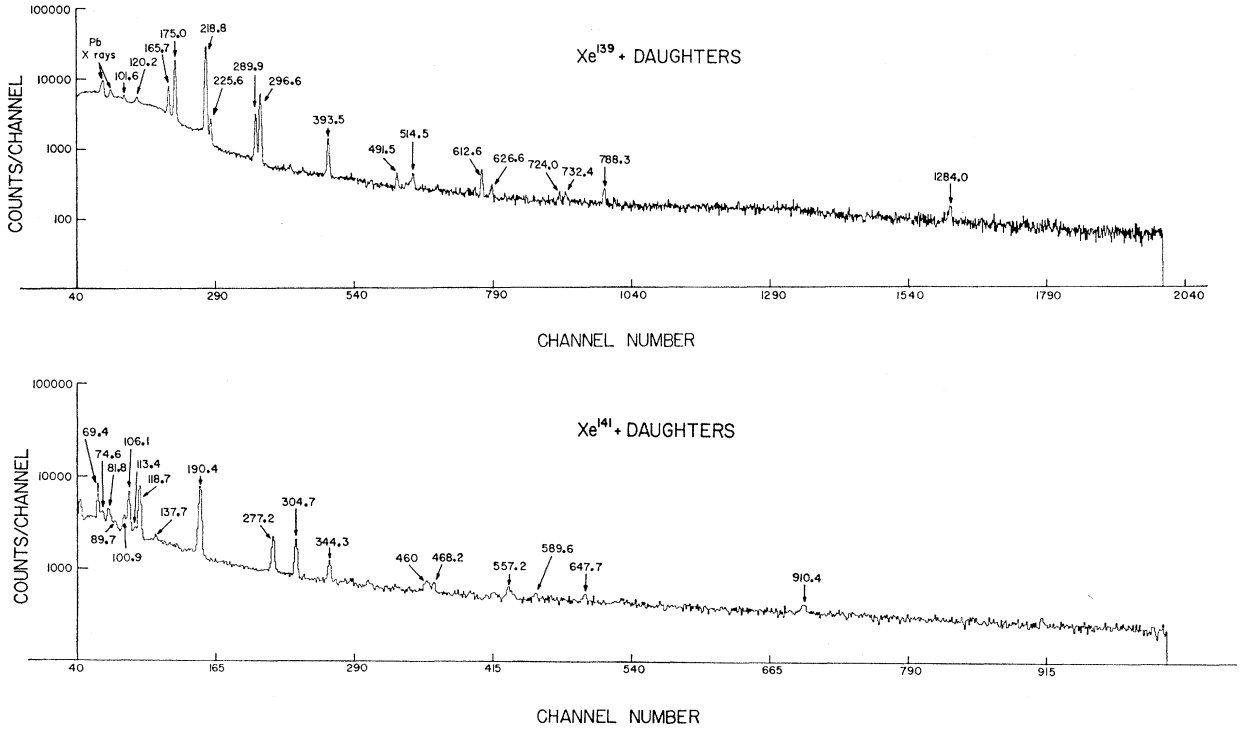


FIG. 5. Upper curve, γ radiation observed from mass-139 decay chain; lower curve, γ radiation observed from mass-141 decay chain.

formula, 6.2 and 7.3 MeV, and from Cameron and Elkin's[9] mass formula, 7.5 and 9.0 MeV, respectively.

γ-Ray Spectra

The γ radiations accompanying the decay of Xe-140 and -142 were observed using both stationary- and moving-tape collection. For Xe-140, the spectrum was also recorded downstream from the collection position, using the moving tape to confirm the assignment of the transitions accompanying Cs-140 decay. The γ spectra of the other Xe isotopes have each been recorded in survey runs using only stationary-tape collection. A summary of the γ-ray energies and relative intensities observed for each mass chain is given in Table III.

In the discussions to follow, we have formulated decay schemes for several of the isotopes investigated in these studies based solely on energy sums and differences. These level schemes advantageously display those numerical relationships and are generally consistent with the available intensity data. We caution that these level schemes are primarily intended to guide the future coincidence studies that are mandatory to establish the correct level structures.

TABLE IV. γ-ray energy (keV).

Parent	This work	Archer[a]
Xe^{138}	154.3	153
	243.1	241
	258.6	258
	396.6	397
	401.5	
	434.2	434
	1768	1769
Cs^{138}	138.3	139.3
	192.5	192.9
	227.9	226.9
	409.1	408.7
	462.6	462.4
	546.6	547.6
	870.7	871.0
	1008.4	1010.2
	2217	2218.7

[a] Reference 12.

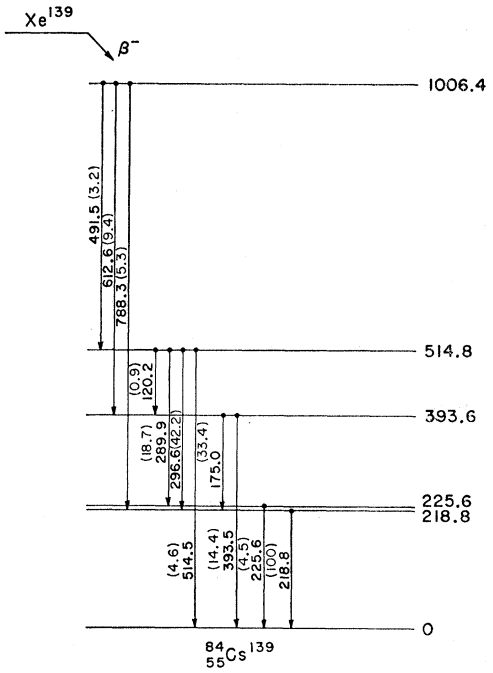


FIG. 6. Tentative level scheme for Cs-139.

Figure 4 shows the γ spectra accompanying the decay of 3.9-min Xe-137 and 17-min Xe-138 and its 32-min daughter Ba-138. We observe only a single prominent γ ray of energy 455 keV in the decay of Xe-137. Ovechkin and Demidovich[10] have reported a γ ray with an energy of 0.44 MeV, using scintillation spectrometry, while Holm and co-workers[11] have reported an energy of 456 keV, together with a number of much weaker transitions not seen in these studies. The mass-138 γ radiations are shown in Table IV, together with the more extensive recent results reported by Archer.[12] A

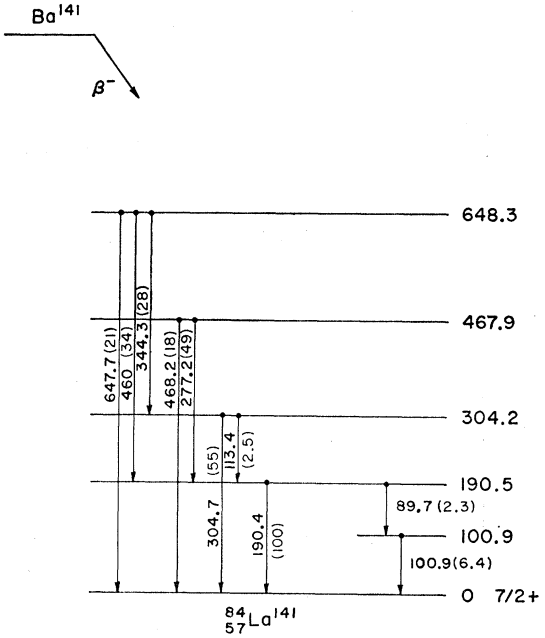


FIG. 7. Tentative level scheme for La-141.

[9] A. G. W. Cameron and R. M. Elkin (privately contributed table).

[10] V. V. Ovechkin and N. N. Demidovich Zh. Eksperim. i Teor. Fiz. **47**, 1671 (1964) [English transl.: Soviet Phys.—JETP **20**, 1123 (1965)].

[11] G. Holm, S. Borg, U. Fägergvist, and F. Kropff, Annual Report, Research Institute for Physics, Stockholm, 1966 (unpublished).

[12] N. P. Archer, thesis, McMaster University, 1965 (unpublished).

comparison of the two γ spectra shown in Fig. 4 show that no significant adjacent-mass contamination ($\leq 2\%$) was experienced under the conditions of these measurements.

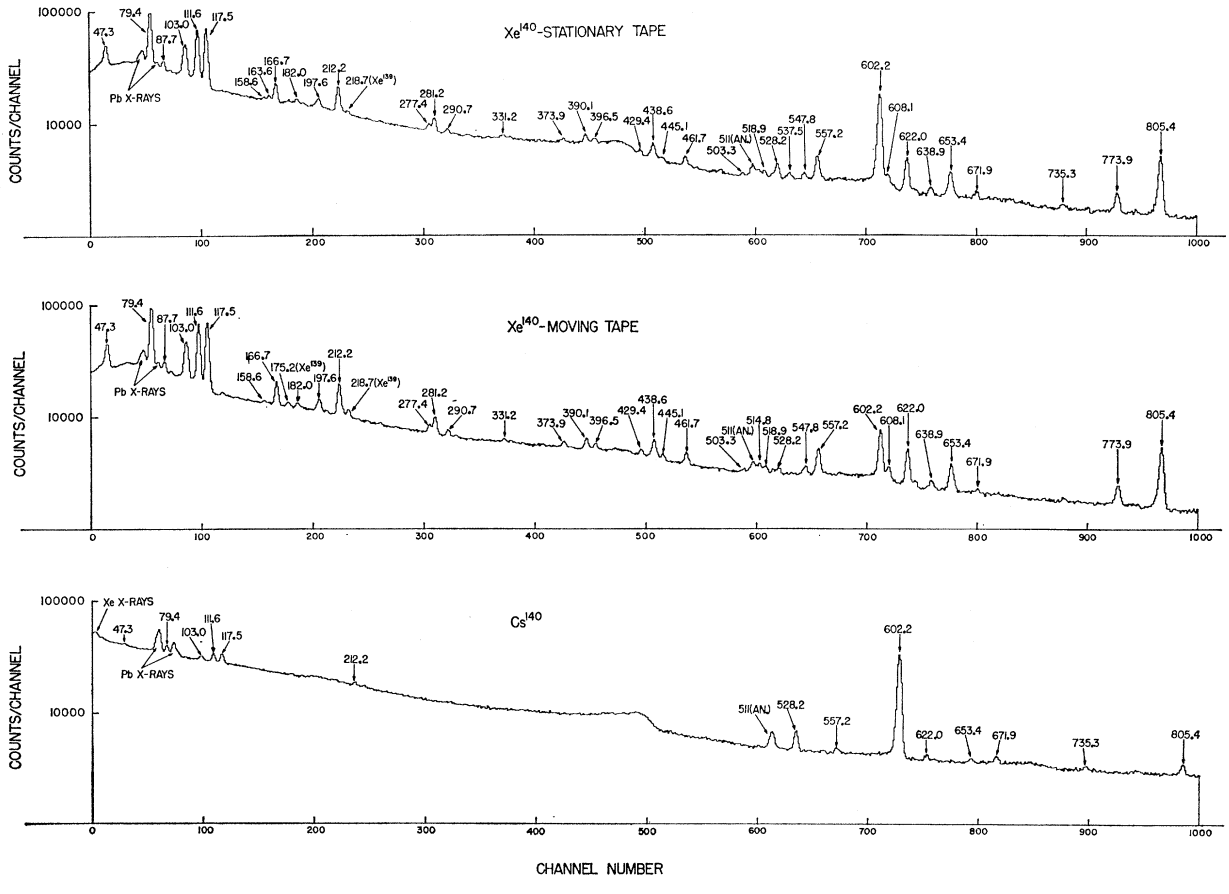
Figure 5 shows the γ transitions associated with the 139-mass chain (39-sec Xe, 9.5-min Cs, and 83-min Ba) and the 141-mass chain (2-sec Xe, 15-sec Cs, 18-min Ba, and 3.9-h La).

Wahlgren[13] has reported γ radiations of 170, 220, 295, and 396 keV to follow the decay of Xe-139 on the basis of scintillation measurements. Our results indicate doublets at 218.8 and 225.6 keV and 289.9 and 296.6 keV separated by 6.7 keV. Using these doublets as a basis, we are able to construct a tentative level scheme for Cs-139 as shown in Fig. 6, which accommodates the transitions at 120.2, 175.0, 218.8, 225.6, 289.9, 296.6, 393.5, 491.5, 514.5, 612.6, and 788.3 keV, and which we assign on this basis to transitions in Cs-139 following Xe-139 decay. The Cs-139 level scheme shown is similar to a recent proposal by Holm and co-workers,[11] with the exception that we propose two close-lying states at 218.8 and 225.6 keV.

Two transitions of 630 and approximately 1275 keV have been reported[13] to follow the decay of Cs-139; these most likely correspond to the 626.6- and 1284.0-keV transitions observed in our spectrum. Similarly, a strong transition of approximately 166 keV [13] has been reported to follow the decay of Ba-139, which is probably the 165.7-keV transition observed in these studies.

In the case of the 141 spectrum, a strong 190-keV transition has been found in La-141 [13] following the decay of the 18-min Ba precursor. We identify this with the 190.4-keV transition observed in our mass-141 spectrum shown in Fig. 5. A number of transitions shown in the spectrum involve 190.4 keV as an energy sum or difference. These can be fit into the La-141 level scheme shown in Fig. 7 and are accordingly assigned to follow the decay of Ba-141.

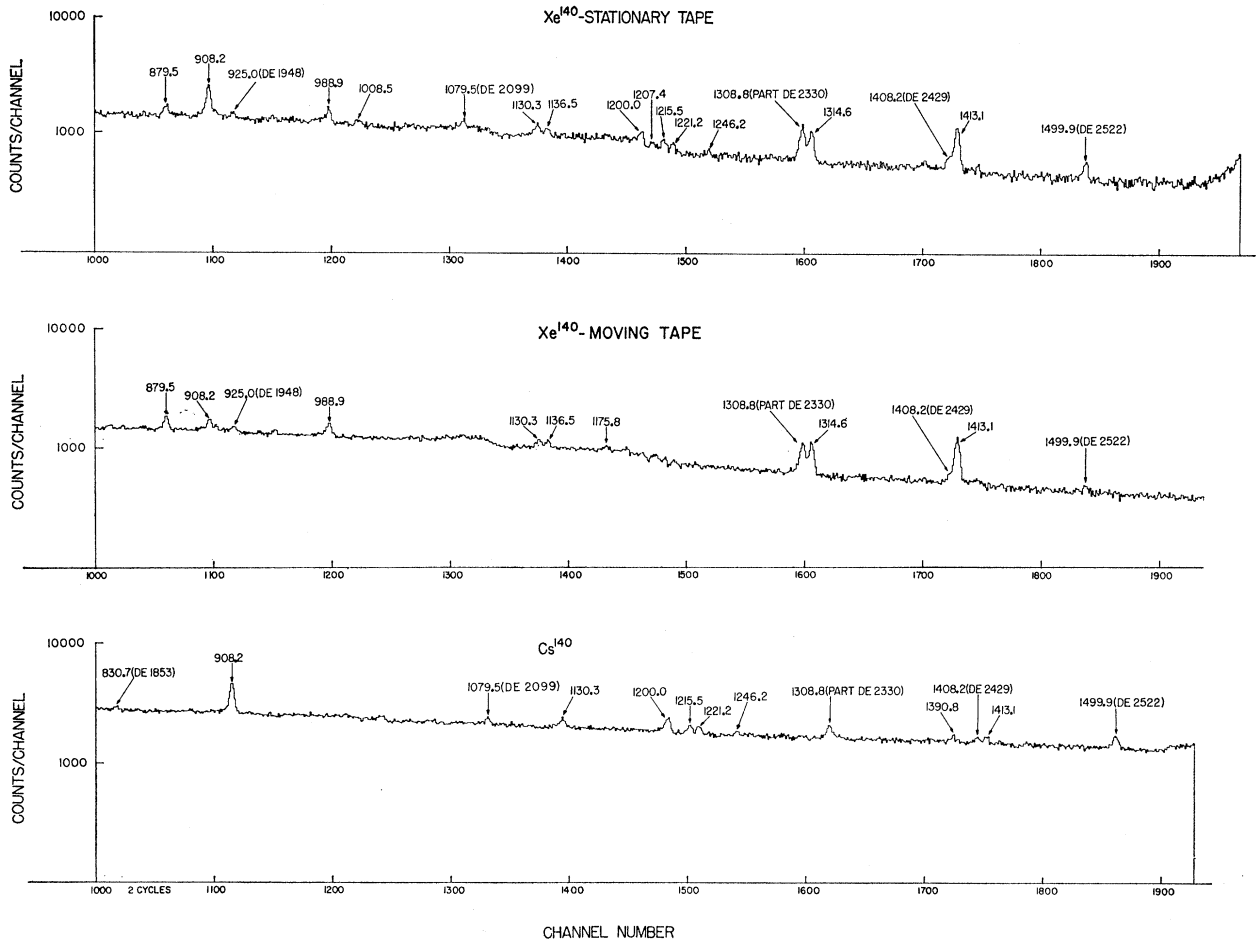
Figures 8–10 show γ spectra observed at mass 140 (14-sec Xe-140 and 64-sec Cs-140), using stationary-



(a)

FIG. 8. γ radiation up to 2 MeV observed from mass-140 decay chain. The first and fourth curves from the top were taken at position I with stationary tape; the second and fifth at position I with moving tape; and the third and sixth at position II with moving tape.

[13] *Nuclear Data Sheets*, edited by K. Way *et al.* (U. S. Government Printing Office, National Academy of Sciences—National Research Council, Washington 25, D. C.) NRC 61-3-88.



(b)

FIG. 8. (*Continued*).

and moving-tape collection. The assignments of transitions listed in Table III are made on the basis of the relative γ-ray intensities observed in these spectra. It is apparent that the dominant transition following the decay of Cs-140 is the 602.0-keV transition, which is assigned to the de-excitation of the first excited state of Ba-140. Zherebin and co-workers[14] have reported a prominent transition of 0.60 MeV to follow the decay of Cs-140 which is in coincidence with a 0.89-MeV transition. This latter γ ray most likely corresponds to the 908-keV transition that we have observed. By noting that a difference of 602 keV occurs between a number of transitions following Cs-140 decay, we propose the level scheme for Ba-140 shown in Fig. 11. Figure 12 shows a tentative level scheme for Cs-140 which accommodates most strong transitions observed.

Figure 13 shows the γ transitions observed in the mass-142 decay chain (1.5-sec Xe, 2.3-sec Cs, 11-min Ba, 1.4-h La), using stationary- and moving-tape collection. By comparison of the two spectra, a single transition of energy 361.0 keV is observed to follow the decay of Cs-142. Accordingly, we assign this transition as depopulating the first excited state of Ba-142. Figure 14 shows a tentative level scheme for Cs-142 which accommodates most strong transitions observed.

CONCLUSIONS

Our survey of the radiations emitted in the decay of short-lived neutron-excess Xe isotopes has demonstrated the feasibility of obtaining detailed nuclear-spectroscopic information from the decay of radionuclides with half-lives as short as 1 sec. The on-line mass-separation technique combined with moving-tape collection has enabled us to sort the very complicated spectrum of γ radiations accompanying the β decay of these mass chains and assign the γ radiations following the decay of the various members. In this way we have determined the energy of the first excited states in even-even Ba-140 and -142 to lie at 602 and 361 keV, respectively. The systematic variation of the energy of the first excited states of the Ba isotopes in the vicinity

[14] E. A. Zherebin, A. I. Krylov, and V. I. Polikarpov, Yadern. Fiz. 3, 981 (1966) [English transl.: Soviet J. Nucl. Phys. 3, 717 (1966)].

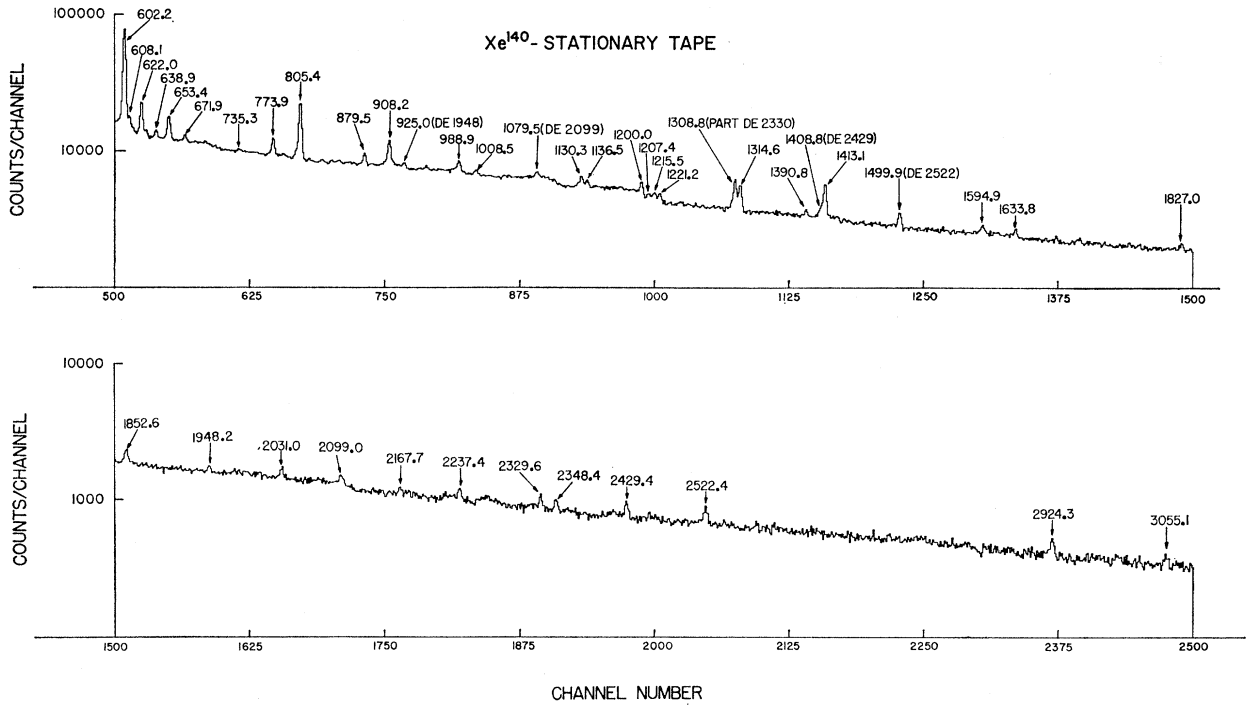


FIG. 9. γ radiation up to 4 MeV observed from mass-140 decay chain at position I with stationary tape.

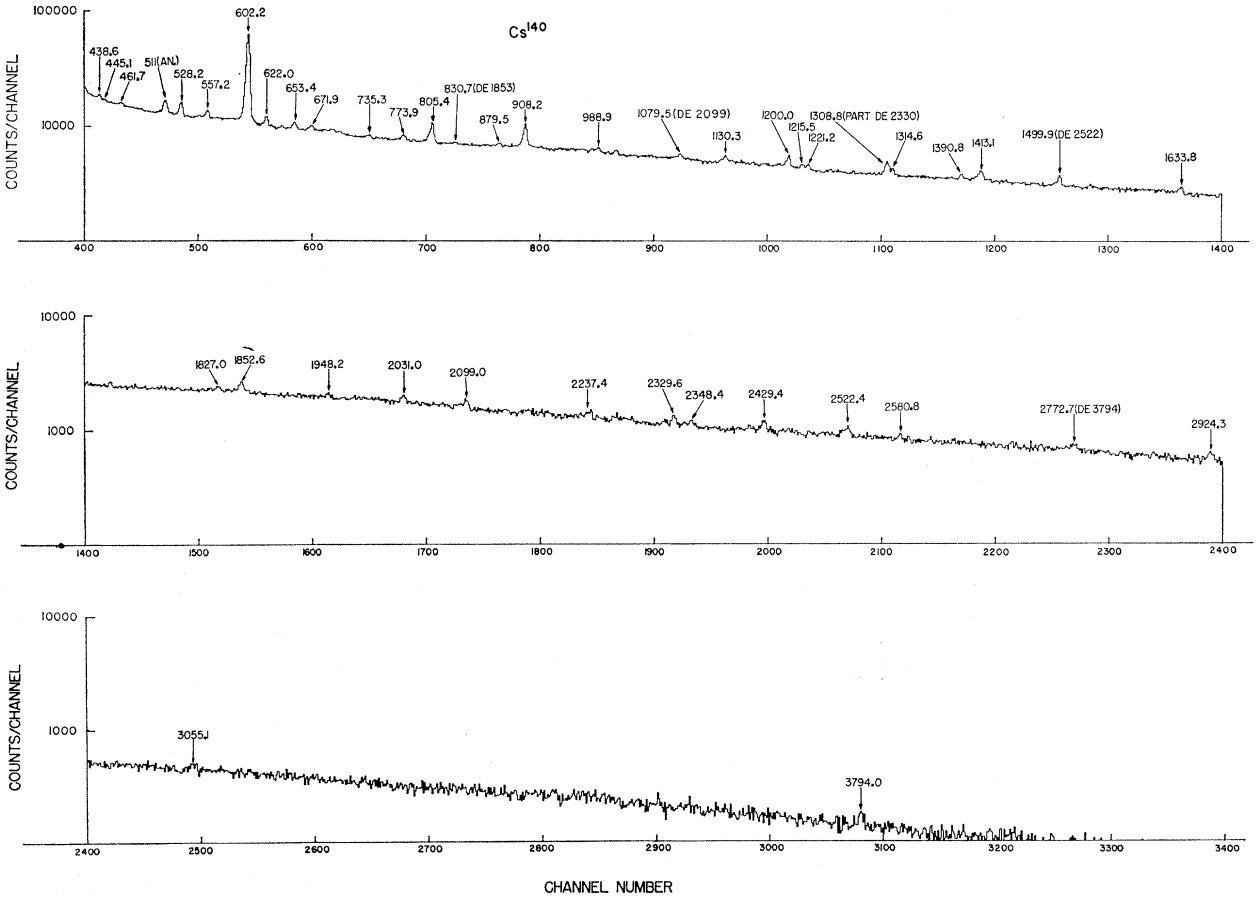


FIG. 10. γ radiation up to 4 MeV observed from mass-140 decay chain at position II with moving tape.

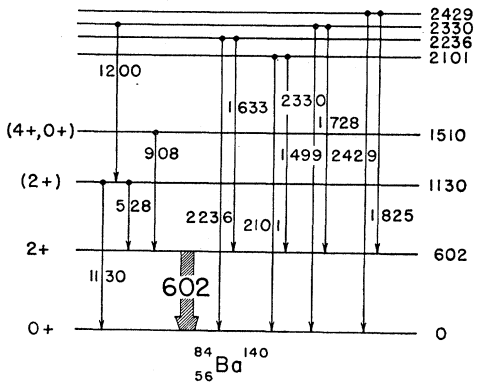


FIG. 11. Tentative level scheme for Ba-140.

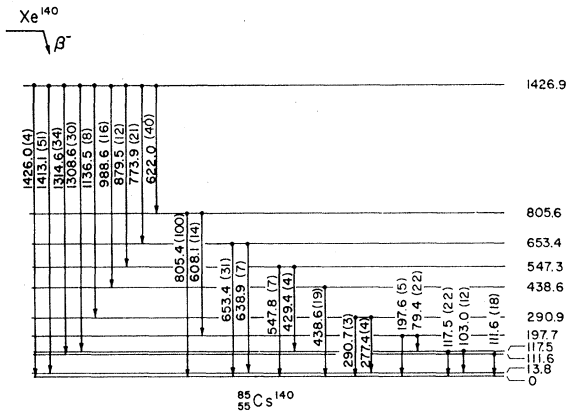


FIG. 12. Tentative level scheme for Cs-140.

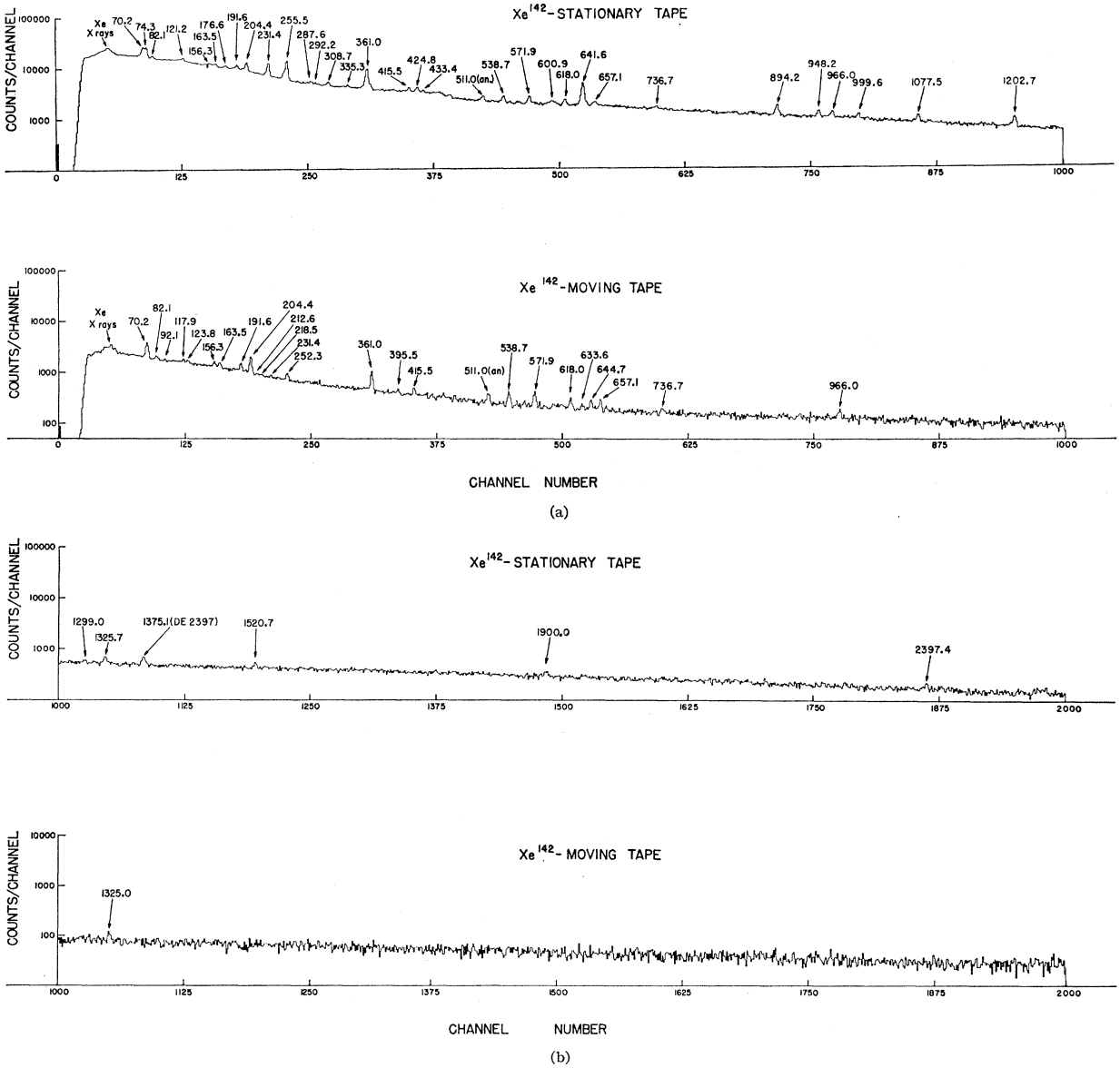


FIG. 13. γ radiation observed from mass-142 decay chain. The first and third curves from the top were taken at position I with stationary tape, the second and fourth at position I with moving tape.

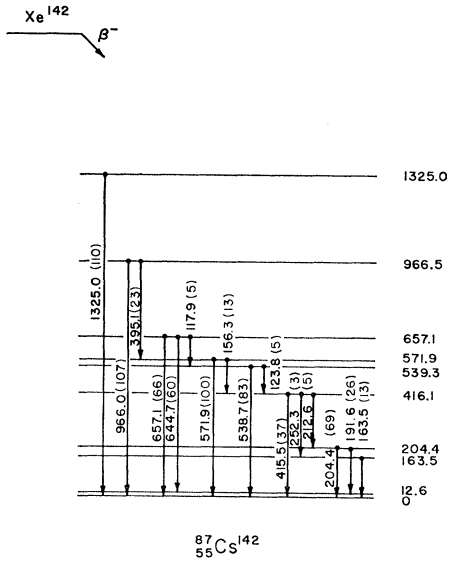


FIG. 14. Tentative level scheme for Cs-142.

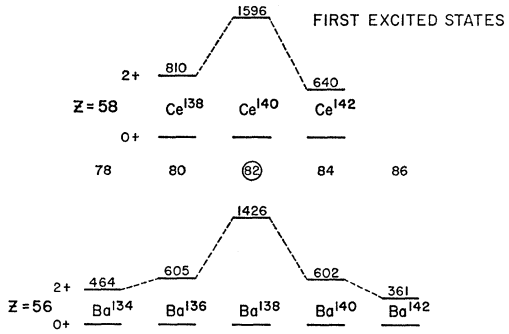


FIG. 15. The systematic variation of the energy of the first excited states of certain Ba and Ce nuclides in the vicinity of the 82-neutron closed shell. Data for Ba-140 and -142 are those found in this work. Other data are taken from *Nuclear Data Sheets* (Ref. 13).

of the 82-neutron closed shell is shown in Fig. 15, where a comparison is made with certain Ce nuclides.

A major difficulty in fitting the γ transition that we have observed into complete decay schemes has been the lack of coincidence data. We have been unable to secure extensive data because of lack of source intensity. From on-line studies now under way using Xe fission products produced in reactors or by using Cf-252 sources one or two orders of magnitude larger than the one employed here, this information will be accessible, particularly if two-parameter coincidence techniques are employed.

The technique as here described is necessarily limited to inert-gas fission products. It would be of particular interest to develop on-line gas-phase chemical or recoil-separation techniques which would make short-lived isotopes of other elements produced in fission accessible for study.

ACKNOWLEDGMENTS

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