Deformation in the Light Ba Isotopes: Isomeric States of Ba^{125} and Ba^{127}†

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The existence of isomeric states and the relative spacing of these levels, in the light barium isotopes associated with the population of $h_{11/2}$ and $s_{1/2}$ or $d_{3/2}$ states, could be an aid in establishing both the sign and the extent of the nuclear deformation, if interpreted in the spirit of the Nilsson levels or the approach of Kumar and Baranger. Isomerism has been observed in the cases of Ba^{125} and Ba^{127}, with the unique characteristic that the high-spin states lie below the low-spin states of the isomeric pair. These isomers have been formed using heavy-ion reactions for direct formation of the high-spin states and from β decay of their parents for the low-spin states. Ba^{125} decays from the high-spin state ($T_{1/2}=3.0\pm0.5$ min) by β^+ ($E_{ww}=4.6$ MeV) to levels at $\sim$20, 76, and 160 keV, while the low-spin state ($T_{1/2}=8\pm1$ min, $E_{ww}=5.5$ MeV) decays principally to the ground state and a state at <30 keV. Ba^{127}, in turn, gives rise to γ rays of 70, 110, 180, and 200 keV, with the high-spin state ($T_{1/2}=18$ min) separated from the low-spin state ($T_{1/2}=10\pm1$ min) by 200 keV. This inversion of the Nilsson states from Ba^{129} would indicate that the deformation is oblate (negative β) and has a value of between 0.11, the point where $h_{11/2}$ crosses $d_{3/2}$-$s_{1/2}$, and $\sim$0.2, where the onset of a $\frac{7}{2}-$ state would present an $E3$ transition between isomers of short half-life.

1. INTRODUCTION

THE existence of isomerism in odd-A neutron-deficient barium isotopes could be an additional supporting point to the speculation that these isotopes mark an onset of a region of nuclear deformation.[1,2] It is recognized, of course, that the mere presence of isomerism itself may not support such a conclusion.

However, the relative spacing of the isomeric states can be interpreted in the framework of the Nilsson energy-level diagrams[3] or as modified by Kumar and Baranger.[4] Then the characteristic spacing and ordering of high- and low-spin isomeric states may serve to define not only the limits within which isomerism is possible with respect to deformation, but also to establish the sign of the deformation parameter. Figure 1 is a representation of the Nilsson scheme as modified by Kumar and Baranger of odd-N even-Z isotopes. The positions of the $h_{11/2}$ single-particle state with respect to either the $s_{1/2}$ or $d_{3/2}$ states for a negative deformation parameter show a characteristic which can be thought of as unique. That is, for an oblate deformation[5] ($\beta=-0.17$) the $h_{11/2}$ state should lie lower than the low-spin $\frac{1}{2}+$ or $\frac{3}{2}+$ levels, requiring an $M4$ radiative transition, and indicative of the presence of isomerism. If, however, the deformation exceeds $\sim$0.26, then a shorter-lived $E3$ transition, because of presence of the $\frac{7}{2}$ level, would prohibit observation of levels other than the $\frac{11}{2}$ ground state (see Fig. 1).

It has been shown that the heavy-ion (HI) compound-nucleus evaporation process demonstrates a marked preference in populating the high-spin member of an isomeric pair,[6,7] and indeed this method of production was used to establish isomerism in a neighboring nucleus, Ba^{129}.[8] Early mass assignments of Ba^{125} and Ba^{127} made either via the (HI,xn) reaction or proton-induced fission[9] show a small but real discrepancy in half-lives. If indeed isomerism exists in Ba^{125} or Ba^{127}, then the half-life measured via milking of the daughter, Cs^{125} and Cs^{127}, may be influenced by the isomer ratios produced by these two mechanisms of earlier studies.

In the present study, advantage was taken of the isomeric production ratios anticipated from the work of Li *et al.*,[8] and Dudey[7] for HI reactions, along with statistical model calculations, which when combined, illustrated that the $In^{115}(N^{14},4n)Ba^{125}$ and $Sb(B^{11},xn)$-Ba^{127} reactions could produce clean samples of sufficient specific activity to establish the relative positions of the isomeric states.

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[1] R. K. Sheline, T. Sikkeland, and R. Chanda, Phys. Rev. Letters **7**, 446 (1961); R. Chanda, J. E. Clarkson, and R. K. Sheline, in *Proceedings of the Third Conference on Reactions between Complex Nuclei, Asilomar, 1963*, edited by A. Gheorso, R. M. Diamond, and H. E. Conzett (University of California Press, Berkeley, 1963).

[2] A. C. Li, P. M. Strudler, I. L. Preiss, and D. A. Bromley, Bull. Am. Phys. Soc. **10**, 441 (1965).

[3] S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. **29**, No. 16 (1955).

[4] K. Kumar and M. Baranger, Phys. Rev. Letters **12**, 73 (1964).

[5] The values of the deformation parameter are not to be considered as absolute, but rather, illustrative of a predicted occurrence of isomerism in this region.

[6] N. D. Dudey, doctoral dissertation, Clark University, 1963 (unpublished).

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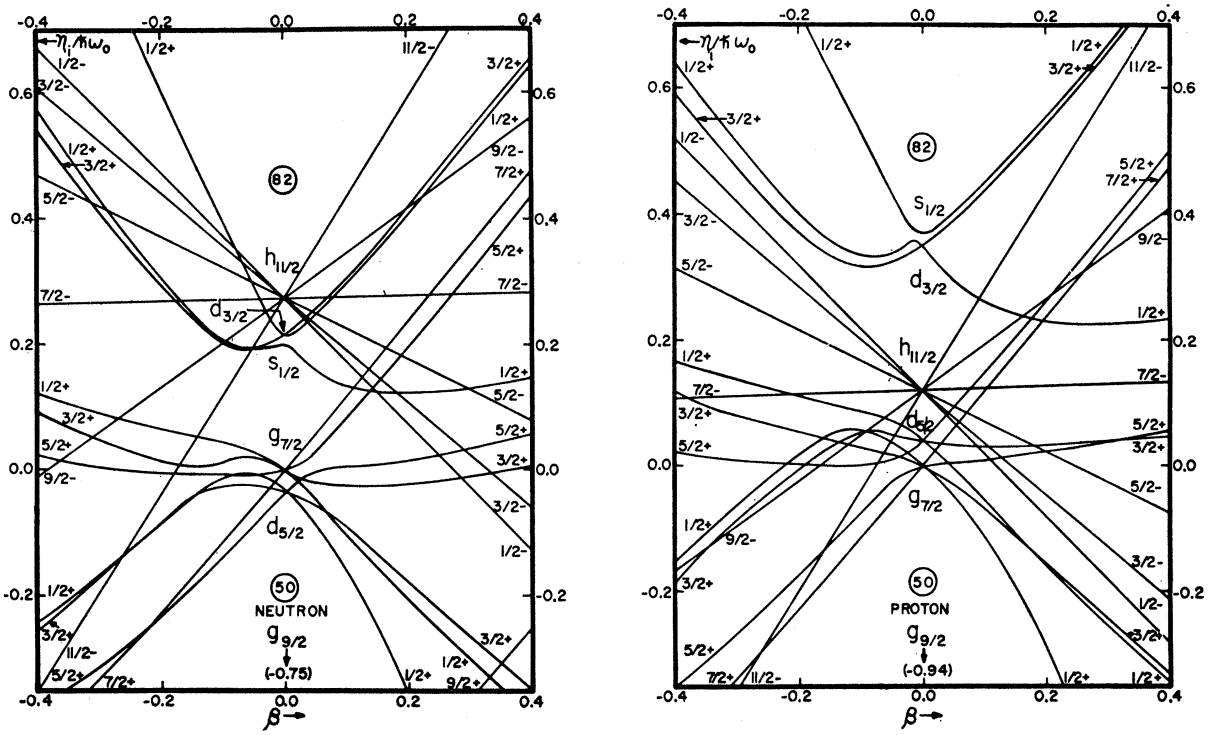


FIG. 1. Excerpt from the Nilsson eigenvalue plot for nucleon number in the range 50–82.

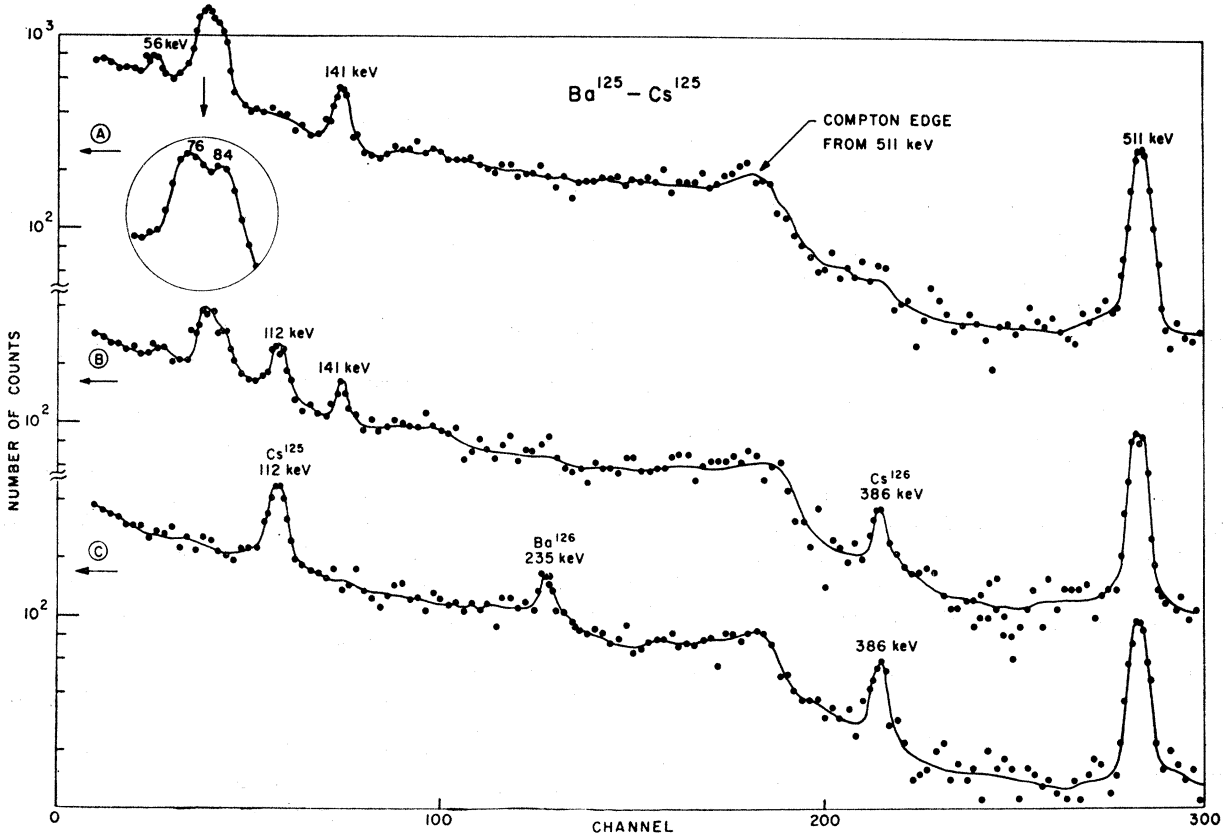


FIG. 2. Representative γ-radiation spectra from the decay of Ba^{125}. The Ge(Li) detector used had dimensions 6 mm thick$\times$6 cm^2 area. Detailed description of these spectra are given in the text.

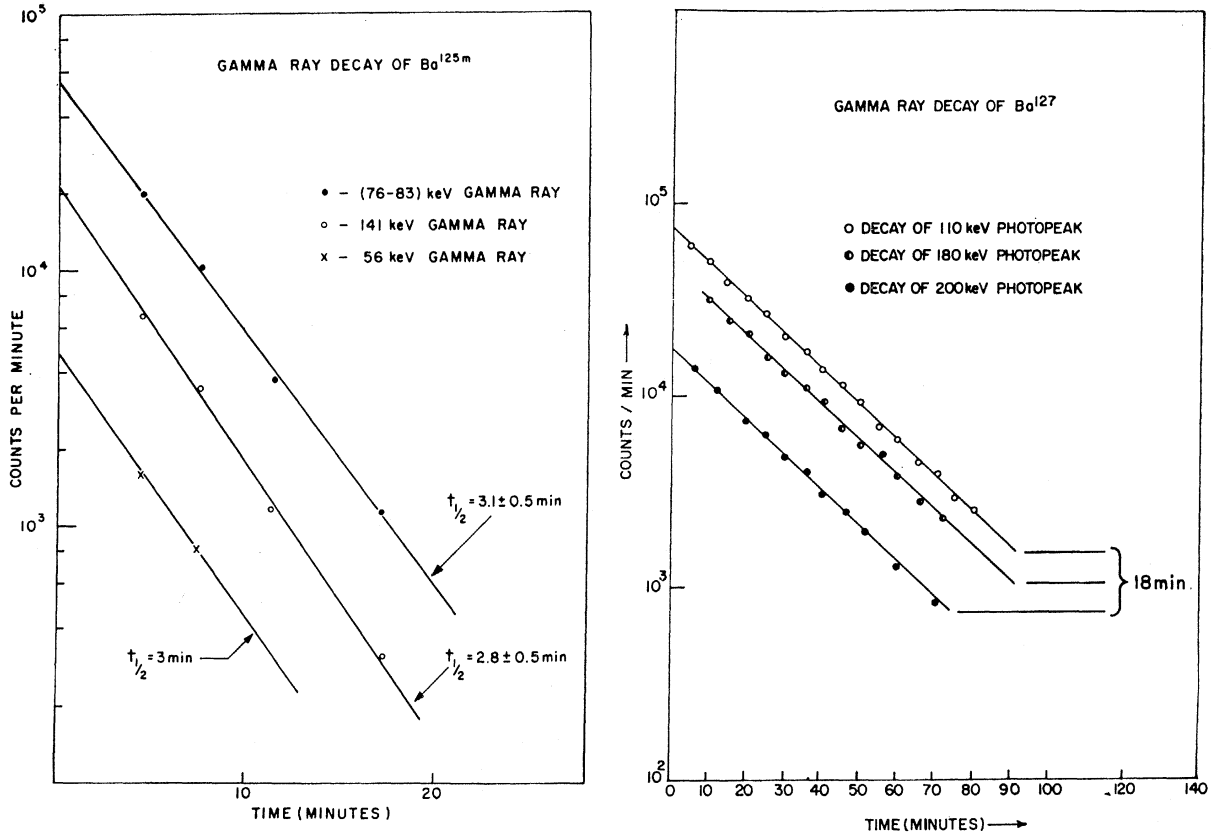


FIG. 3. (a) Half-life of the (76-83)- the 141-, and the 56-keV γ rays. (b) Half-life of the 110-, the 180-, and the 200-keV photopeaks as followed in a single-channel analyzer.

2. SAMPLE PREPARATION

The reactions employed to produce Ba^{125} or Ba^{127}, as written above, were studied at several beam energies so as to establish the validity of the calculated excitation functions[10] for specific mass assignments and to determine the radiations associated with other neutron-deficient isotopes in this region.[11] Two different targets were employed. In cases where high specific activity but minimum isotopic selectivity were required, thick natural indium or antimony targets ($\sim$37 mg/cm^2) were used, thus integrating over a large portion of the excitation function. In these cases the indium or antimony foil acted as both target and recoil catcher. When maximum purity was desired, as well as for cross-section measurements, thin targets (1.0–1.5 mg/cm^2) were utilized, with the recoiling products stopped in aluminum catcher foils of appropriate thicknesses. The beam energy desired was produced using aluminum degrading foils preceding the target, correlated with the range-energy data of Northcliffe.[12] Bombardment times were chosen to minimize the yield of interfering adjacent radionuclides such as Ba^{126}. That is, an enrichment factor of at least 7 in specific activity of Ba^{125} over Ba^{126} was achieved in a 1-min irradiation, even when thick targets were employed. By using beam energies below 65 MeV (determined in preliminary experiments), the production of the more neutron-deficient isotope, Ba^{124}, was eliminated in the case of Ba^{125}. For Ba^{127} formation, little if any Ba^{125} was produced from the Sb targets when incident B^{11} energies of 62 MeV were employed.

Targets were dissolved in a 1:1 HCl:HNO_3 mixture (aluminum catcher foils in a heated solution of concentrated HCl), appropriate hold-back carriers added, and barium precipitated as $Ba(NO_3)_2$. After centrifuging, the supernate was discarded and the $Ba(NO_3)_2$ redissolved in a minimum amount of H_2O buffer solution. The barium was then reprecipitated as either the chromate or sulfate.

In experiments designed to milk the cesium daughter, the final precipitation was eliminated and after addition of excess chloroplatinic acid, cesium was precipitated

[10] R. Black, doctoral dissertation, MIT, 1964 (unpublished).
[11] J. M. D'Auria, Ph.D. thesis, Yale University, 1967 (unpublished).
[12] L. C. Northcliffe, Ann. Rev. Nucl. Sci. 13, 67 (1963).

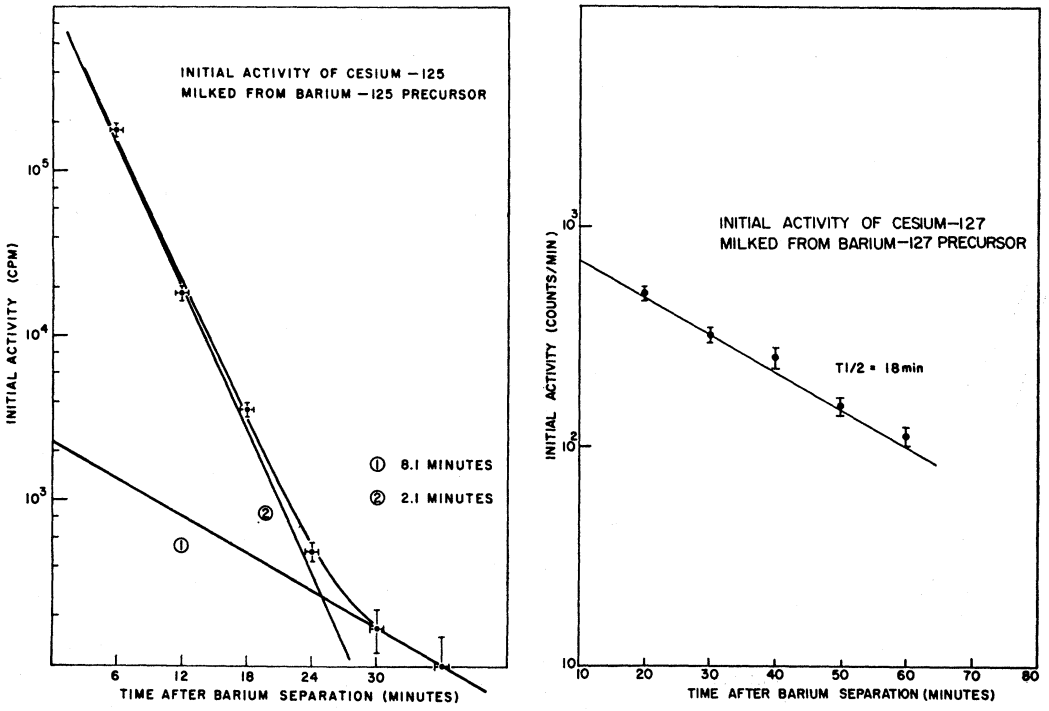


FIG. 4. The initial β-decay activity of Cs chemically separated at fixed time intervals from the chemically pure Ba fraction. Each point represents the Cs activity extrapolated to the time of chemical separation. The decrease in Cs activity with the time of separation is a measure of the decay constant of the parent. (a) illustrates the Ba^{125}-Cs^{125} equilibrium and (b) depicts the results of theBa^{127}-Cs^{127} parent-daughter relation.

at regular time intervals as the chloroplatinate. Each precipitate was weighted to establish chemical yields before counting.

The direct de-excitation of the compound system produced an enhanced yield of the high-spin states of Ba^{125} and Ba^{127}. In order to compliment these studies the low-spin member of the pairs was populated through the β decay of its precursors La^{125} and Ce^{127}-La^{127}. That is, in the O^{16} irradiation of indium, La^{125} was formed via the $In^{115}(O^{16},6n)La^{125}$ process. The barium formed via $In(O^{16},pxn)Ba$ reaction was chemically separated and then, after a suitable decay period, barium daughter activity was separated and counted. In the case of Ba^{127}, O^{16} irradiations of Sb yielded Ce isotopes. Again, as in the direct process by adjusting the incident beam energy, irradiation time, and times of the chemical separation, the Ba^{127} resulting from the β-decay chain

$$Ce^{127} \xrightarrow{\beta^+} La^{127} \xrightarrow{\beta^+} Ba^{127}$$

could be isolated and counted.

In the case of Ba^{127}, very clean samples could be produced in this way. That is, little if any, of the high-spin state resulted, since the $Sb(N^{14},\alpha xn)Ba$ process that would populate this state had either a very small cross section or did not preferentially populate the high-spin state as in the $Sb(B^{10},xn)Ba$ decay of the Ba compound system. Because of the half-lives involved and the apparent yield of the high-spin state of Ba^{125} via $In(O^{16},pxn)Ba$, the Ba^{125} sample contained both high- and low-spin state with only an enrichment of the low-spin member.[11]

In studies requiring the summing of more than one sample, each sample was normalized with respect to beam intensity, target thickness, chemical yields, etc.

3. SPECTROSCOPY

γ-ray spectra were accumulated using a Ge(Li) detector having a depth of 4 mm and a cross-sectional area of 6 cm^2. In addition, use was made of both 3×3- and 4×5-in. NaI(Tl) detectors, either singly or in coincidence with other NaI detectors or the Ge(Li) detector. Typical coincidence resolving times were 40 nsec. Thin NaI(Tl) crystals (2×$\frac{3}{4}$ in.) were employed in studies of the K x rays (30 keV). The L x-ray half-lives were followed utilizing a large side-window gas-flow proportional counter. Gross β-decay curves were obtained with an end-window gas-flow proportional counter and/or a large plastic scintillator. This later crystal, exhibiting a linear response for β rays up to 13 MeV with a resolution of 200 keV, was employed to establish the β-ray endpoint energies and in β-γ coincidence studies. For β endpoint work, the triple coincidence system (511-511-β) as described by D'Auria

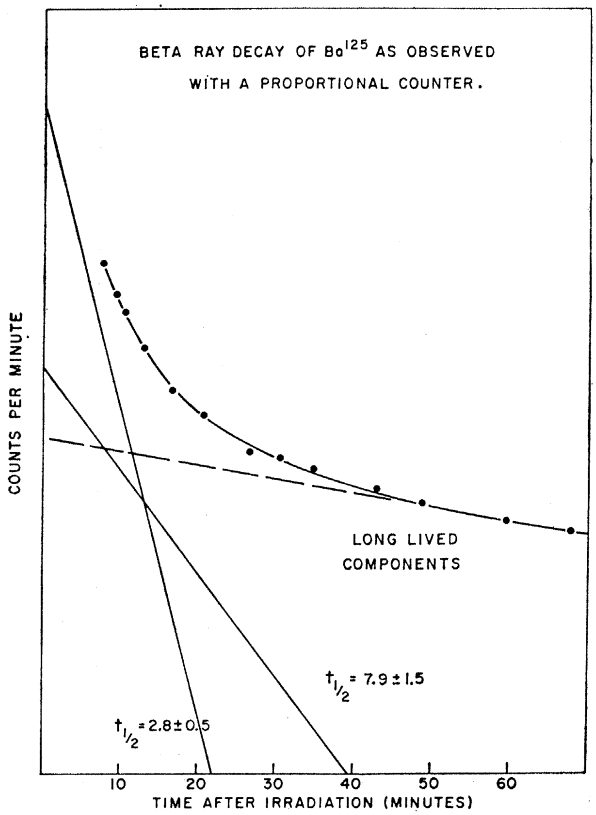


FIG. 5. The gross β-decay curve observed with a proportional end-window β counter.

and Preiss[13] was incorporated to minimize distortion of β-ray spectra caused by summing effects. All β endpoint energy measurements include the crystal resolution of 200 keV as a systematic error, since no attempt was made to correct the energy response for the resolution.

4. RESULTS

Barium-125

Typical γ-ray spectra, as obtained with the Ge(Li) detector, are represented in Fig. 2, taken at 4.5, 11.5, and 48 min after the end of bombardment. Previously unobserved and unassigned γ rays resulting from the decay of Ba^{125} were detected at 56±3, 76±2, 84±2, and 141±2 keV, decaying with a composite half-life of 3.0±0.5 min (see Fig. 3). The presence of Cs^{125} (112-keV γ ray) indicated the production of the precursor, while the only other isobaric chain, produced at this bombardment energy with yields greater than 5% of the total activity, was 126. These points, coupled with the results of the milking experiments (represented in Fig. 4) and the relative γ-ray yield versus incident beam energy, led to the assignment of these γ rays to the decay of Ba^{125}.

[13] J. M. D'Auria and I. L. Preiss, Nucl. Phys. 84, 37 (1966).

Studies of the high-energy portions (>600 keV) using the NaI(Tl) detectors placed an upper limit of 5% on the relative intensities of transitions other than those observed in the Ge(Li) spectra.

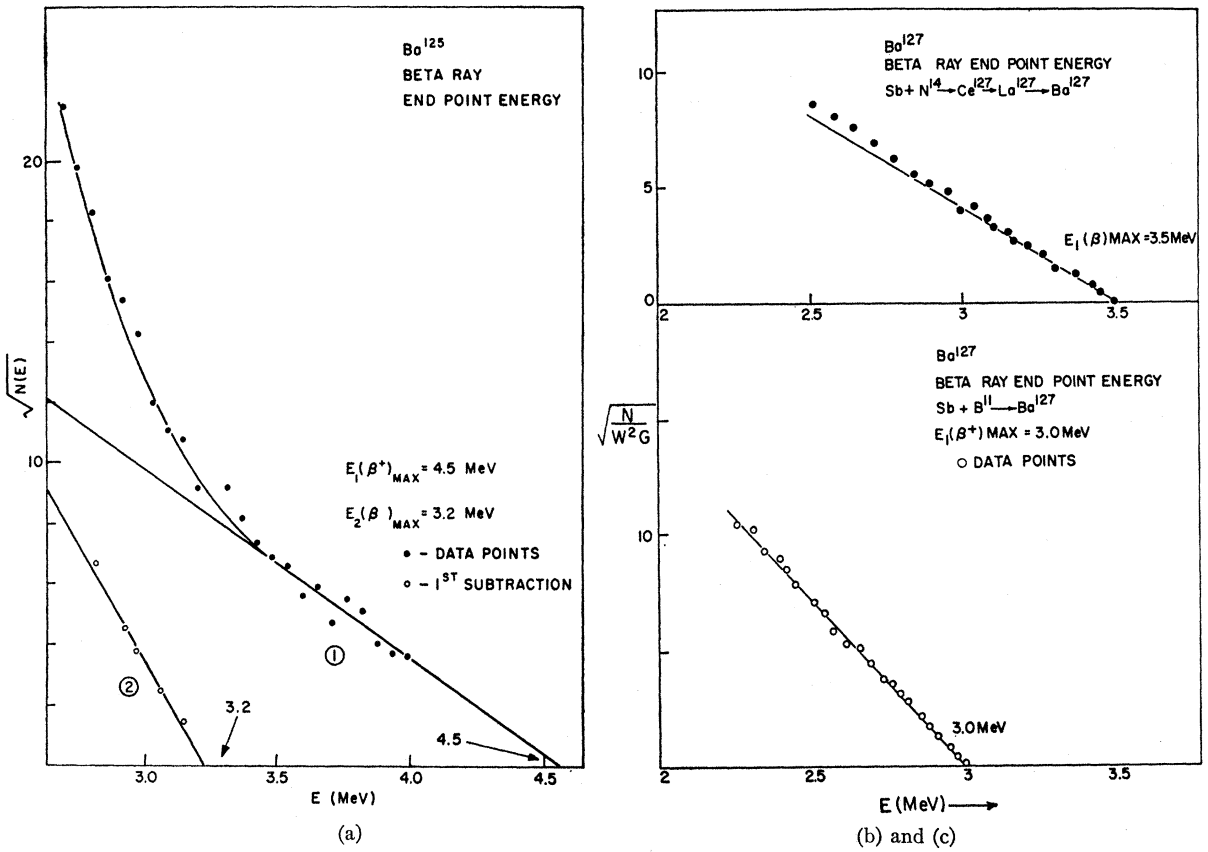
The gross β counting performed on similar samples using the proportional counters yielded previously unobserved half-lives of 2.8±0.5 and 8±1.5 min (see Fig. 5), in agreement with the results of the milking experiments. β-energy spectra were collected with the thick plastic phosphor for a period of only 8 min to reduce interference from the longer-lived components. The highest-energy component present in these spectra was 4.5±0.3 MeV and the next 3.2 MeV (see Fig. 6).

Two multichannel analyzers recorded the β-ray and γ-ray energy spectra from the plastic phosphor and Ge(Li) detector simultaneously. These detectors were calibrated in both energy and total counting efficiency. The observed β-ray spectra were analyzed by plotting the integrated number of β-energy pulses; (a) greater than 511 keV, and (b) in selected energy increments, versus the time after irradiation. The γ rays with 3-min half-life were associated with the low-energy β particles from Ba^{125} with their maximum energy lying in the range of 2.9–3.3 MeV. With the presence of only the 8-min component and the 100-min component (Ba^{126}) in the highest-energy segment (3.3–4.7 MeV), the 4.5-MeV β particle observed previously was unambiguously assigned to the 8-min component. This component, which was also observed in the annihilation quanta decay, and in the milking experiments, was assigned to the decay of Ba^{125}.

The thick plastic phosphor and the thin NaI(Tl) crystal (used as the gating signal) were incorporated to determine the energy of the positrons in coincidence with the γ rays associated with the 3-min level of Ba^{125}. Figure 7 depicts the observed β spectrum (summed over 7 samples) in coincidence with a γ energy window of 70–90 keV; the E_{max} (β^+) present is 3.4±0.25 MeV. This energy value agrees with the results of the β-spectrum half-life studies for those β particles having a half-life of 3 min. Summing the coincident γ-ray energies and the annihilation energy of 1.02 MeV, the total energy available for β decay of the 3-min level of Ba^{125} is 4.6±0.25 MeV. Since the 8-min state has an

TABLE I. Observed γ-ray energies, their relative intensities, and coincident γ rays for Ba^{125} and Ba^{127}.

	Results of the γ-γ coincidence				
	Ba^{125}		Ba^{127}		
Energy of the gate (keV)	Relative intensity	Coincident γ-rays energy (keV)	Energy of the gate (keV)	Relative intensity	Coincident γ-rays energy (keV)
56	5	~20, 84	70	50±20	(20), 110
76	100	84	90	20±5	110
83	86	~20, 56, 76	110	110±10	(20), 70, 90 180, 200
141	42	≤30			
368	...		180	50±10	(20), 110
112	...		200	18±7	110
386	...				



(a) (b) and (c)

FIG. 6. (a) Fermi-Kurie plot of a β spectrum of Ba^{125}. (b) Fermi-Kurie plot of the β spectrum of Ba^{127} produced via β decay of $Ce^{127} \rightarrow La^{127} \rightarrow Ba^{127}$. (c) Fermi-Kurie plot of a β spectrum of Ba^{127} produced after bombardment of Sb with B^{11} ions.

energy of 5.5±0.3 MeV, there remains about 900±300 keV for the isomeric level separation.

Because it was suspected that the low-energy γ transitions would be highly internal-converted, the decay of the K and L x rays was followed. In these studies, no 8-min activity was detectable in the gross decay of K x rays, but was found in the L x-ray spectrum decay along with the 3-min activity.

γ-γ coincidence studies were performed using the Ge(Li) detector and NaI(Tl) crystal. The results of these studies proved: (a) the observed γ rays were only populated by decay of the 3-min level of Ba^{125}, (b) coincidence exists between the 76–83, 56 (76 and 83), and 141–368 keV γ rays, and (c) a weak γ transition exists at about 368 keV. These results are listed in Table I.

Barium-127

Typical γ-ray spectra obtained with the Ge(Li) detector, taken 5 min after the end of bombardment, are presented in Fig. 8. γ rays were detected at 70±2, 90±2, 110±2, and 200±2 keV, all decaying with half-life of 18±1 min (see Table I) and subsequently assigned to the decay of Ba^{127}. The presence of Cs^{127} (406-keV γ ray) indicated the production of the precursor, while the only other isobaric chain, produced at this bombarding energy yield greater than 10% of the total activity, was 126. These points, in addition to the results of the milking experiments (represented in Fig. 4) and the relative γ-ray yield versus incident beam energy data, led us to assign the above γ rays to the decay of Ba^{127}.

Studies of the high-energy photons (>500 keV) using the NaI(Tl) detector placed an upper limit of 5% on the relative intensities of transitions other than those observed in the Ge(Li) spectra. The sum spectrum, taken with a 3×3-in. NaI(Tl) detector, showed enhancement in the relative intensity of 200-keV photopeak as compared to 110 or 180 keV. The low-energy portion of the γ-ray spectrum with NaI(Tl) detector showed two γ rays of 70 and 90 keV. The 20-keV photopeak could not be resolved from the 30-keV Cs x rays.

Gross β counting performed on similar samples using the proportional counters yielded a half-life of 18±1 min (see Fig. 9), in agreement with the results of the milking experiments. The β-ray spectrum analysis was performed using a thick plastic phosphor. Several samples were counted one after another, each for 10 min, to increase the statistics and to reduce the interference

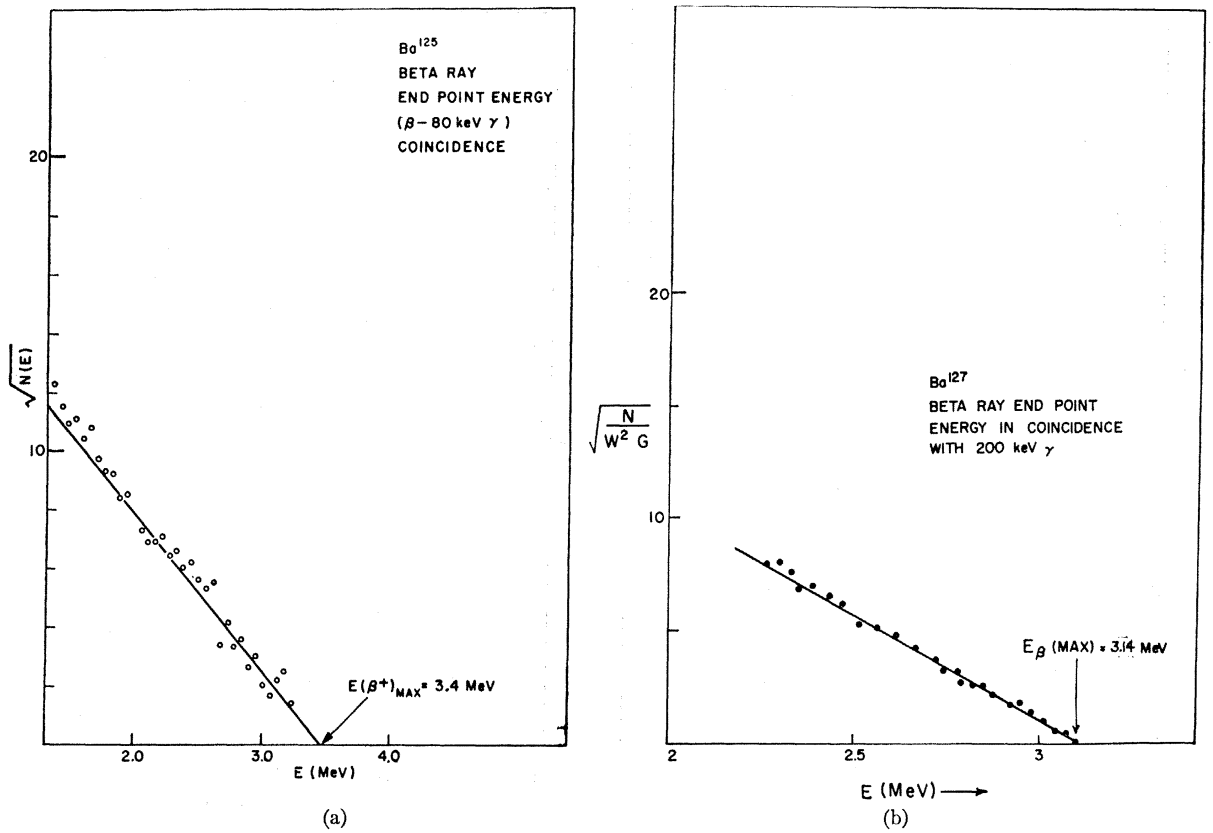


FIG. 7. (a) β spectrum of Ba^{125} in coincidence with 80-keV γ ray. (b) β spectrum of Ba^{127} in coincidence with 200-keV γ ray.

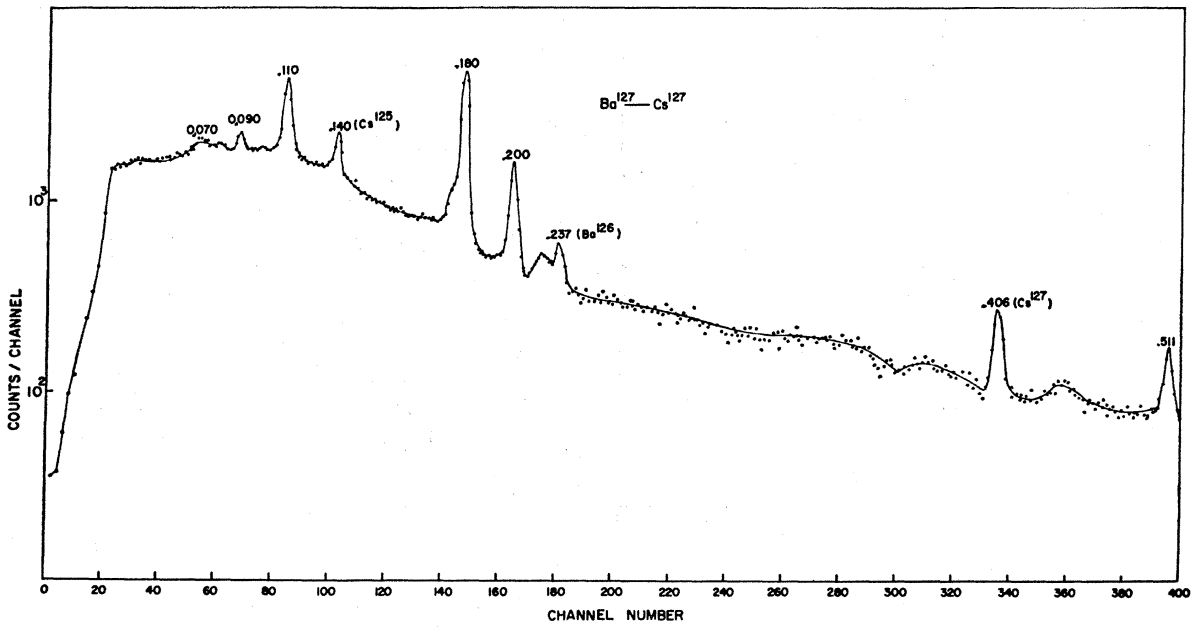


FIG. 8. Typical γ-ray spectrum of Ba^{127} as obtained with the Ge(Li) detector. The source was chemical-separated Ba fraction after bombardment of Sb with B^{11} ions.

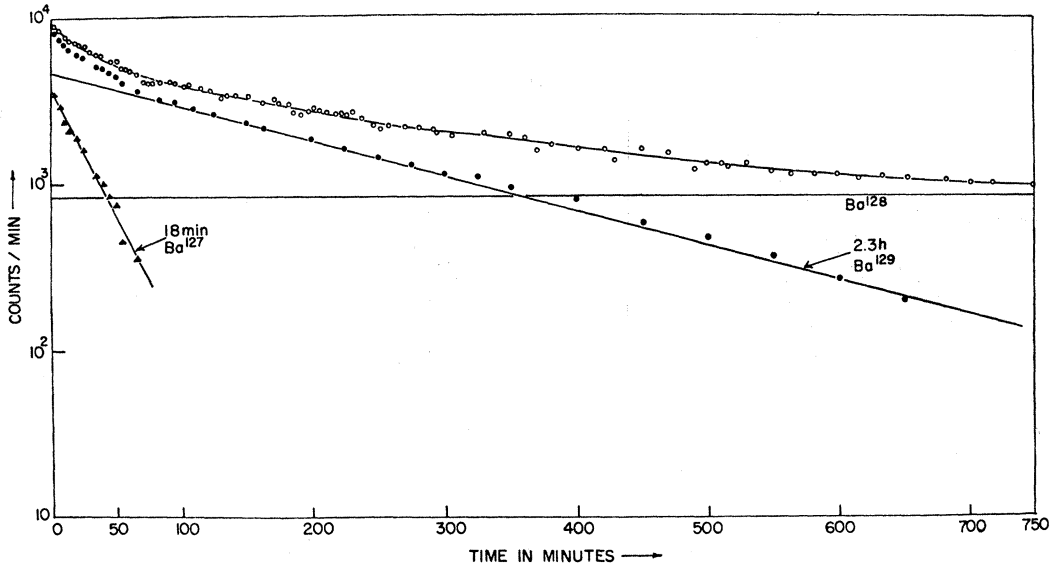


FIG. 9. Gross β-decay curve of Ba^{127} (low-spin state) obtained with a proportional counter.

from the longer-lived components. The highest β end-point obtained was 3.0 MeV (see Fig. 6).

Sources of Ba^{127} were also produced through the β decay of its precursors ($Ce^{127} \rightarrow La^{127} \rightarrow Ba^{127}$). Thick Sb targets were bombarded with N^{14} beams for a period of 5 min. Chemical separation of Ba was done after a fixed period of 10 min to allow the formation of Ba^{127}. The gross β counting performed on these samples using proportional counters yielded a half-life of 10 min but only a negligible contribution of the 18-min activity

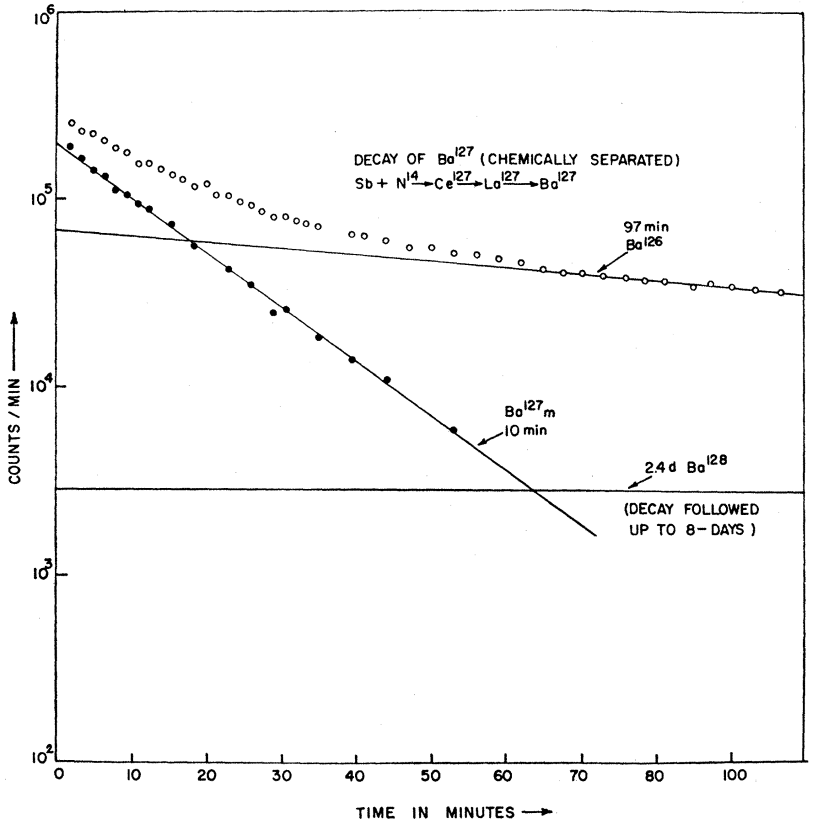


FIG. 10. Gross β-decay curve of Ba^{127}. The source was produced by $Ce^{127} \rightarrow La^{127} \rightarrow Ba^{127}$ β-decay chain.

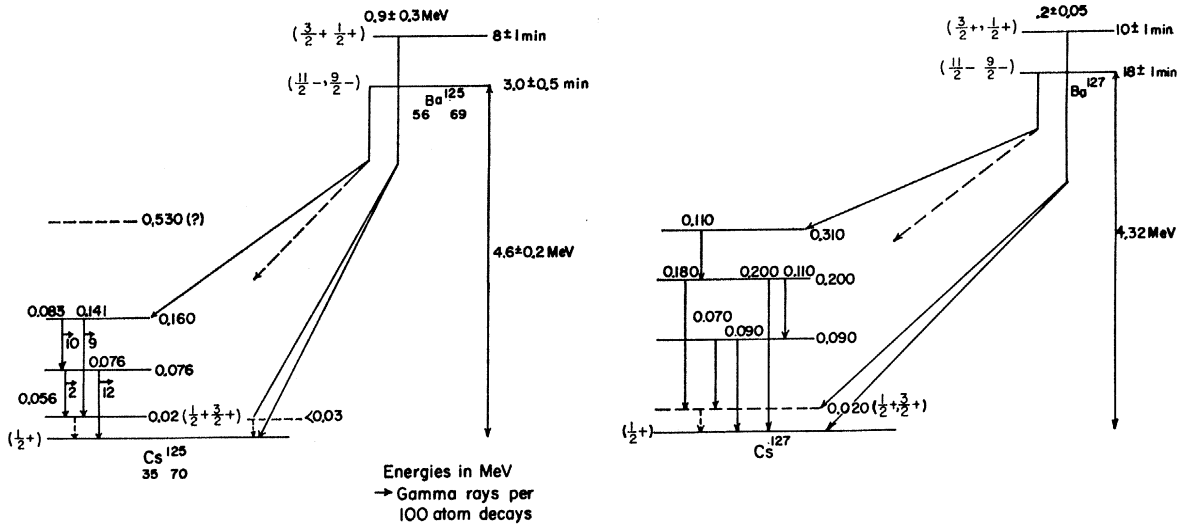


FIG. 11. Proposed decay schemes of Ba^{125} and Ba^{127}.

(see Fig. 10). The milking experiments, as described above, and the presence of Cs^{127} led to the assignment of this half-life to the isotope Ba^{127}. The β-ray spectrum analysis on these sources yielded an endpoint energy of 3.5 MeV (see Fig. 6). The γ-ray spectrum showed no photopeaks of greater than 30 keV, allowing us to conclude that the 10-min Ba^{127} isomer decays mainly to the ground state of Cs^{127}.

The thick plastic phosphor and the thin NaI crystal (used as the gating signal) were incorporated to determine the energy of the positrons in coincidence with the γ rays emitted by the 18-min isomeric level of Ba^{127}. Figure 7 shows the observed β spectrum (summed over 12 samples) in coincidence with the 200-keV photopeak. The analysis of the β-ray spectrum gave an endpoint energy of 3.1 MeV, which agrees with the results of the β half-life studies for those particles having a half-life of 18 min. The total energy available for the β decay of the 18-min level of Ba^{127} to Cs^{127} was 4.3 MeV, and with the 10-min state having an energy of 4.5 MeV, there remains about 200 ± 50 keV for the isomeric level separation.

γ-γ coincidence studies were performed using two well-shielded 3×3-in. NaI(Tl) detectors whose axes were perpendicular. The results of these studies proved: (a) The observed γ rays were only populated by the decay of the 18-min level of Ba^{127}, and (b) coincidences exist between the (70-110)-, (90-110)-, (110-110)-, (110-180)-, and (110-200)-keV γ rays (see Table I).

5. DISCUSSION

The presence of isomerism in both Ba^{125} and Ba^{127} is clearly indicated by the two components appearing in the gross β decay, the associated annihilation radiation and the milking of the cesium daughters. The half-lives deduced for the isomeric states of Ba^{125} are 3.0 ± 0.5 and 8.0 ± 1 min with maximum energies available for β decay of 4.6 ± 0.3 and 5.5 ± 0.3 MeV, respectively. The half-lives found for Ba^{127} are 18 ± 1 and 10 ± 1 min with maximum β-decay energies of 4.3 ± 0.2 and 4.5 ± 0.2 MeV, respectively. The yields of these states indicate that the 3-min component in Ba^{125} and the 18-min component in Ba^{127} are approximately three times those for the 8-min (Ba^{125}) and 10-min (Ba^{127}). Since the 3- and 18-min isomers are more strongly populated via the compound-nucleus process, they have been assigned as the high-spin components of these isomeric pairs. In this case, the low-spin member of Ba^{125} lies above the high-spin ground state by 900 ± 200 keV, and in Ba^{127} the low-spin state again is above the high-spin state by approximately 200 keV. In both cases, the low-spin member appears to decay exclusively to the ground state (or a state at <30 keV) in the cesium daughters.

The energy states involved in these isomeric pairs based on any reasonable model arise from the $h_{11/2}$ and the $s_{1/2}$ or $d_{3/2}$ shell-model orbitals. Thus, any isomeric transition would involve a parity change indicative of an $E3$ or $M4$ transition. The fact that no isomeric transition was observed with an intensity limit of 5×10^{-2} of the β-decay branch implies that the partial lifetime of this process is $\sim5\times10^{3}$ sec. Barring a very extraordinary retardation for an $E3$ transition (factor of 10^{7} based on the single-particle estimates), the transition in question is most probably of the type ($\Delta J=4$, yes) or $M4$. This argues for an assignment of $(\frac{1}{2}+,\frac{3}{2}+)$ and $(\frac{9}{2}-,\frac{11}{2}-)$ to the isomeric state and the ground-state configuration of $Ba^{125,127}$, respectively.

Standard arguments were used in deducing the partial decay schemes shown in Fig. 11. The interpretation of the level schemes, however, is far from clear. For purposes of brevity, only the excited levels of Cs^{125} are discussed, recognizing that similar arguments are appropriate for Cs^{127}. The allowed nature of

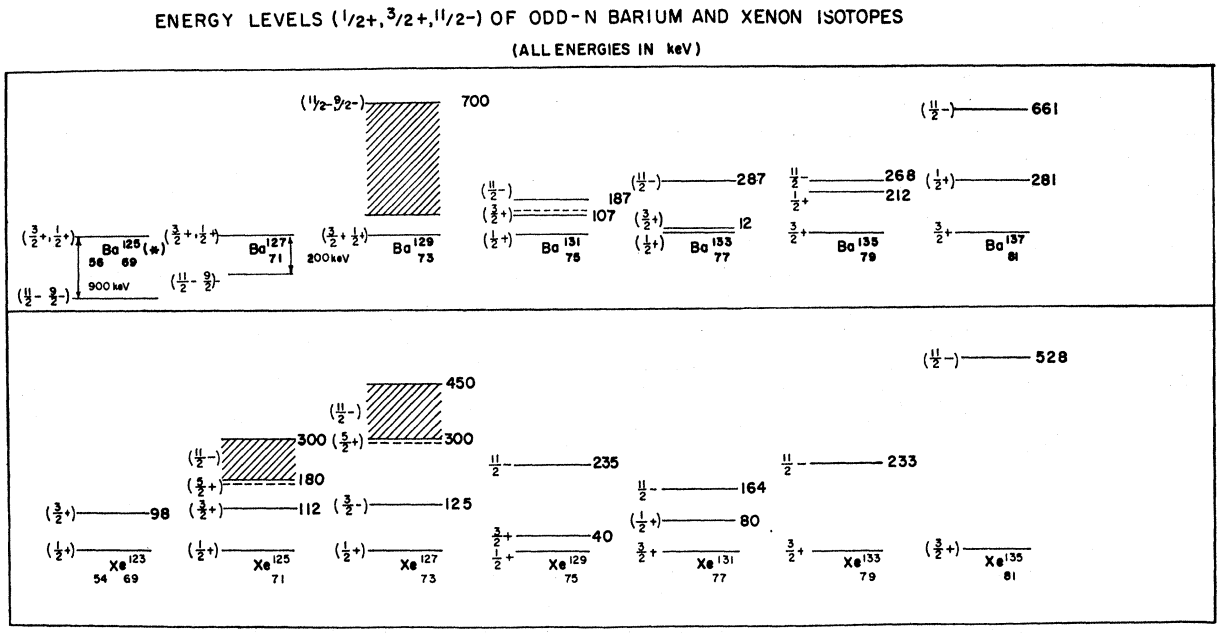


FIG. 12. Relative level spacing in odd-A neutron-deficient Xe and Ba isotopes based in part on data from Ref. 11. The decrease in energy spacing between the $h_{11/2}$ and low-spin states of Ba, with an eventual inversion, should be noted. The reverse effect for the Xe isotopes is apparent.

the β decay from the high-spin negative-parity ground state implies that the levels at 160 and 310 keV in Cs^{125} and Cs^{127}, respectively, are probably both negative-parity configurations. The implication of the values from the low-spin members indicates low-spin positive parity for the ground state and the state at $\sim$30 keV in Cs^{125} (and Cs^{127})[14] (implied via observation of the L x rays and the 76-55-keV energy difference). If one assumes a $\frac{9}{2}-$ value for the high-spin isomer, then the 160-keV level would be expected to have a spin of $\frac{7}{2}-$ ($\Delta J=1$, no) at the lowest. The de-excitation of levels in Cs^{125} to the states at $\sim$20 and 76 keV would of necessity involve an $M2$ or $E3$ transition, if one assumes that this $\sim$20-keV level is indeed the same one populated in the low-spin state allowed β decay. The state at 76 keV could be of spin $\frac{5}{2}+$ since it does not seem to be populated by the low-spin isomer (exhibiting the 8-min β^+ decay). Presuming that the state at 20 keV is common to both the feeding from above and the β^+ decay of the 8-min Ba^{125} (and 10-min Ba^{127}) low-spin ($\frac{1}{2}+$) parent, this would argue for a $\frac{1}{2}$-, $\frac{3}{2}$-, $\frac{5}{2}$-spin sequence with a $\frac{7}{2}$-state the first level in a $K=\frac{9}{2}$ band, giving ($\Delta K=0$, no) for the β decay of the high-spin member of the isomeric pair. An identical argument can be used in discussing the spin sequence of the excited levels in Cs^{127} and a similar conclusion arrived at. The presence of a level above 20 keV in Cs^{127} indicates that the level at 30 keV in Cs^{125} could conceivably be a doublet (see above), or that the level at 310 keV in Cs^{127} has spin higher than ($\frac{7}{2}-$). No further conjecture is warranted with the present data, however.

6. CONCLUSIONS

The general treatment given by Nilsson[3] and its subsequent extension by Kumar and Baranger[4] predict the existence of isomerism in the Ba-La region. It would seem appropriate, then, to choose to formulate the conclusion of the basis of the levels predicted by the latter, rather than attempting to extend such approaches as those of Kisslinger and Sorensen.[15]

The existence of isomerism in Ba^{129} had been attributed to the population of the $h_{11/2}$ and $s_{1/2}$ or $d_{3/2}$ states.[8] This configuration, with the absence of any intermediate spin state, can exist only for oblate deformation at least. Referring to Fig. 1, for oblate deformations the $h_{11/2}$ level decreases in energy, and finally become the ground state at a value of $\beta=-0.17$ for the deformation parameter. At a greater deformation, one expects that the $\frac{7}{2}-$ projection of the $h_{11/2}$ state would produce a spin sequence giving rise to a fast isomeric transition ($E2$, $E3$ and/or $M2$), thereby precluding the presence of the relatively long-lived isomers observed in this study. Therefore, on the basis of this model we are able to deduce that the magnitude of the deformation lies between $\beta=-0.17$ and -0.25 and is oblate, if the isomerism observed does indeed result from the $h_{11/2}$ and $s_{1/2}$ or $d_{3/2}$ states.

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It is interesting to note that the values of β deduced from direct observation of the de-excitation γ cascade in Ba^{126} [16] and those deduced from lifetime measurements in Ba^{128} [17] (both even-even nuclei) indicate a deformation greater than that which can be inferred from the existence of, and energy relation between the isomeric states in Ba^{125} and Ba^{127}. However, it is not clear whether these earlier measurements or those reported here refer to the natural ground-state configuration or are merely indicative of the deformability in the excited states. It would appear that the deductions based on the relative spacing of the isomeric levels would more realistically approach the picture of the true ground-state configurations.

At this point, it is not at all clear as to the origin and detailed nature of what appears to be negative-parity excited states at 160 keV in Cs^{125} and 310 keV in Cs^{127}. The allowed nature of the β decay from the high-spin negative-parity precursors seems to require this spin assignment $(\frac{7}{2}-)$, however. And again, the absence of states at energies above a few hundred keV cannot be explained in the framework of existing information.

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Ternary Fission of U^{238} Induced by Intermediate-Energy Helium Ions*

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Evidence is presented for the existence of ternary fission of a heavy excited nucleus into three fragments of comparable size from radiochemical studies on U^{238} bombarded with 20–120-MeV helium ions. The absolute formation cross sections for Na^{24}, Mg^{28}, Si^{31}, S^{38}, Ca^{47}, Mn^{56}, and Ni^{66} in the (39±1)-MeV He^4-induced fission of U^{238} clearly establish the transition region between binary and ternary processes, the crossover occurring around $A=47$. The corresponding data for Ta^{183} and Ta^{184} and upper limits for Au^{199}, Pb^{209}, and Pb^{212} also indicate the absence of any possible complimentary heavy fragments. The fission-product nature of the light ternary fragments was confirmed by the forward-to-backward recoil properties. The excitation function for the formation of Mg^{28} and the ratio $\sigma_{Mg^{28}}/\sigma_{total}$ drop very rapidly below an excitation energy of 20 MeV, making it highly unlikely that such light fragments can be observed at lower excitation energies. These conclusions are consistent with the previously reported lack of radiochemical evidence for the possible thermal-neutron-induced ternary fission of U^{235}, but are inconsistent with the claims to the contrary based on purely instrumental measurements. The mass-yield curve appears to be smooth in both the ternary and low-mass binary regions, and gives no indication of any "fine structure" in the ternary region.

The recoil properties of Mg^{28} and Sr^{89} studies in the 40–120-MeV energy range indicate close similarities. A mean recoil range of 12.2±0.4 mg/cm² in uranium was obtained for Mg^{28}, corresponding to an average kinetic energy of 45–50 MeV based on similar heavy-ion range-energy data.

I. INTRODUCTION

SPECULATIONS concerning the possibility that a heavy excited nucleus might divide into three fragments of comparable mass, i.e., ternary fission, were made by Present and Knipp[1] shortly after the discovery of nuclear fission by Hahn and Strassmann[2] in 1939. Since that time experimental evidence for ternary fission has been sought by a variety of techniques, particularly by examination of fission tracks in nuclear emulsions impregnated with fissionable nuclides. Emission of small masses such as tritons, He^4, and other light fragments with $Z\leqslant 3$ and $A<10$ are also considered by some authors[3] as a type of ternary-fission process. Much of the earlier work on these light "ternary"-fission products has been summarized previously.[4–7] However, very light fragments can also result from direct interaction not involving a cooperative nuclear phenomena such as is responsible for larger fragment fission.

The first reported evidence for ternary fission into three fragments of comparable mass was that of Tsien

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