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ABSTRACT

The internal conversion electron spectrum accompanying the decay of 11.5-d Ba^{131} has been reinvestigated, and a total of 32 transitions observed. On the basis of energy sums and relative intensities a consistent decay scheme is proposed with levels at 78.6, 123.7, 133.5, 215.8, 372.8, 584.8, 619.6, 696.3 and 1046.5 keV. These results clarify the coincidence data of other workers. The multipolarities of some transitions have been established by making use of experimentally determined L-subshell ratios, K/L ratios and internal conversion coefficients. Delayed coincidence measurements tend to confirm the 13.3-ns half-life for the 133.5 keV level.

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1. Introduction

The radiations emitted in the electron-capture decay of 11.5-d Ba^{131} have been studied by several groups of workers.[1] The first energy level scheme was proposed by Cork et al. on the basis of energy sums, obtained from measurements of the internal conversion electron spectrum with 180° permanent magnet spectrometers.[2] These authors suggested levels at 78.7, 133.4, 373.5 297.5, 621 and 713 keV. The levels at 497.5 and 713 keV required a triple cascade of the 215.8, 123.8 and 373.5 keV transitions. However, by sum-coincidence techniques, Lu et al. later showed that these three transitions were not in coincidence, and proposed levels at 123, 214, 372 and 618 keV.[3] Using similar techniques, Beggs et al. confirmed the latter results.[4] The coincidence experiments of Vartapetian,[5] in addition to supporting the scheme of Lu et al.[3] showed the existence of a level at about 1030 keV. Additional confirmation of the level structure of Cs^{131} as proposed by Lu et al.[3] and Vartapetian[5] was provided by August et al.[6] and Haskins.[7] August et al.[6] also presented evidence for a level at about 703 keV, which was later corroborated

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by Haskins[7] and Bodenstedt et al.[8]

A summary of the work of the forementioned authors, as well as others, shows considerable disagreement as regards the intensities and characteristics of many transitions involved in the decay of Ba^{131}. Hence, the spin and parity assignments of many of the levels in Cs^{131} are not yet firm.

Recently, Person and Rasmussen have attempted to fit the experimental data by applying the asymmetric rotor model to odd-mass nuclei.[9] While they obtained fairly good agreement with the experimentally determined energy levels in Cs^{131} a more detailed comparison was not possible due to a lack of experimental data.

The present investigation was undertaken with the hope of clarifying a number of the experimental discrepancies, as well as to obtain sufficient data to test further the calculations of Person and Rasmussen.

2. Source Preparation

Samples of barium nitrate (enriched to 16.7% in Ba^{130})† were irradiated in a thermal flux of 4.7×10^{14} neutrons cm^{-2} sec^{-1} in the Materials Testing Reactor (MTR), Idaho Falls, Idaho, for periods of 3 to 6 weeks. Sources for the permanent magnet spectrographs (PMS) were made by evaporating a dilute nitric acid solution of the source material on to 0.25-mm diameter platinum wires. The specific activities of these sources (BaO) were approximately 30 mc/mg at the start of the spectrometer runs. For the double focusing spectrometer measurements, BaO was vaporized onto 0.025-mm thick aluminum strips, 1 mm x 15 mm for the iron-free spectrometer, and 2 mm x 9 mm for the iron-core spectrometer. Sources for scintillation studies were liquid-deposited onto thin microscope-slide glasses.

† Obtained from the Stable Isotopes Division, Oak Ridge National Laboratory.

3. Apparatus

The internal conversion electron spectrum of Ba^{131} was measured with 180° permanent-magnet, photographic-recording spectrographs having field strengths of 50, 100, 150 and 340 gauss, with momentum resolution of approximately 0.1%.[10] In most cases, relative intensities of the conversion lines were determined with a 25-cm, double focusing, iron-core spectrometer (DFIC), operated at a resolution of about 0.5%. The detector consisted of a flowing-methane proportional counter with a 0.0063-mm, gold-coated mylar window ($\approx$ 950 $\mu g/cm^2$). Some measurements to determine L-subshell ratios, energies, and relative intensities were performed with the new Berkeley iron-free spectrometer (IF) with the baffles set to operate at a resolution of about 0.17%. Since these measurements were made prior to the completion of the spectrometer cooling system, they were restricted to energies of less than 200 keV.

Photon spectra were measured with a 7.6 cm x 7.6 cm NaI(Tℓ) crystal placed in a 7.6-cm thick lead house (internal dimensions 61 cm x 61 cm x 107 cm) lined with cadmium and copper graded absorbers. Additional measurements were taken with a 3.8 cm x 2.5 cm NaI(Tℓ) crystal which had a 0.013 mm beryllium cover. The lifetime measurements were performed with 25 mm x 3 mm and 5 cm x 5 cm NaI(Tℓ) crystals and a fast-slow coincidence system, in conjunction with a 400-channel pulse-height analyzer. The fast coincidence circuit consisted of a pulse-overlap type time-to-height converter.

4. Internal Conversion Electron Spectrum

The Ba^{131} internal conversion electron spectrum taken with the DFIC spectrometer is shown in fig. 1. Some weak electron lines (not seen previously) are indicated on expanded scales in insets. The L-subshell spectra of the 55.0-, 123.7- and 133.5-keV transitions were measured with the IF spectrometer, as well as with the PMS.

In table 1 are summarized the electron energies, conversion shells, transition energies, and relative electron intensities as determined in this work. In most cases, the energies listed are those measured with the PMS (relative precision about 0.2%). The precision attained for the few energies determined with the IF spectrometer was strongly limited by the source thickness. In general, the data from the PMS were only analysed for relative intensities when these could not be obtained from the other spectrometers. The transitions with energies of 82.4, 137.1, 156.9, 246.3, 294.0, 323.9, 350.3, 426.7, 452.0, 461.1, 480.4, 573.1, 674.2, 696.5 and 914.1 keV, as well as a number of the conversion shells of already established transitions, have not been observed previously in the electron spectrum of Ba^{131}.

Also listed in table 1 are the results obtained by August et al. who used a DFIC spectrometer.[6] The agreement, in most cases, is seen to be quite good; however, our value for the intensity of the K-133.5 line is considerably higher. This discrepancy is probably due to the higher transmission of our counter window for low energy electrons.

5. Photon Data

The photon spectrum of Ba^{131}, as measured in the lead cave with a 7.6 cm x 7.6 cm crystal at a source to crystal distance of 20 cm, is shown in fig. 2. Analysis of the photon spectrum was performed in the usual manner of obtaining single photon spectra under the same conditions, and performing successive subtractions starting at the high-energy end of the spectrum. The areas of the photopeaks were measured and corrected for absorption and relative photopeak efficiencies.[11] The resulting relative photon intensities are given in table 2. It should be noted that the intensities of the 156- and 620-keV photons have been corrected (approximately 10%) for solid angle addition. To determine the relative K X-ray intensity, a separate experiment

was performed in which a barium source was chemically purified and the photon spectrum was measured with a 3.8 cm x 2.5 cm crystal that had a beryllium cover. This measurement took place approximately 4 hours after the chemical separation, and the relative K X-ray intensity so obtained, and given in table 2, has been corrected for the small amount of xenon K X-ray from the decay of the daughter Cs^{131} that had grown in during that time. In correcting the K X-ray intensity account was also taken of the escape peak caused by the K_β X-rays whose energy is greater than the K binding energy in iodine. This correction amounted to about 6%.

For comparison, we have also listed in table 2 the photon results of Campbell.[6] As can be seen, some values agree quite will with those obtained by Campbell, but in other cases there are deviations of more than 20%.

6. Conversion Coefficients and Multipolarities

The multipolarities of a number of transitions in Cs^{131} have been inferred from comparisons of the K/L ratios, L-subshell ratios, and internal conversion coefficients with the theoretical values as computed by Rose,[11,12] and the results are given in table 3. Except where noted, the conversion coefficients have been obtained by normalizing the internal conversion electron and photon intensity data to a theoretical K-conversion coefficient of 0.02 (50% E2 + 50% M1) for the 372.8-keV transition. This normalization was adopted since the 372.8-keV photon was almost completely resolved in the photon spectrum and the theoretical E2 and M1 K-conversion coefficients lie within 20% of each other, thus introducing at most a 10% error.

The 123.7-keV Transition

Use was made of three independent data for the multipolarity assignment of the strongest transition, i.e., 123.7 keV. Comparison of the experimental K/L ratio of 3.0 to the theoretical values of 3.0 and 8.4 for an E2 and M1 transition, respectively, indicates that the 123.7-keV transition is of

multipolarity E2. The L-subshell ratios for this transition were determined in both the PMS and IF spectrometers. Although we obtained good agreement between the results from the two instruments, the errors involved in the individual determinations should be noted. For the PMS, one has to visually infer the relative intensities from the photographic plates, and we estimate the error in the relative intensities so obtained to be $\lesssim$ 20%. We estimate the uncertainty in the decomposition of the L-lines measured in the IF spectrometer to be about 15%. With this in mind, one can compare the experimentally determined L-subshell ratios, $L_I/L_{II}/L_{III}$ = 1/1.25/1.35, to the theoretical values 1/1.32/1.40 and 1/0.072/0.017 for an E2 and M1 transition, respectively. The agreement between the experimental and theoretical E2 values, supports the E2 assignment for the 123.7-keV transition, although a possible M1 admixture ($\approx$8%) cannot be completely ruled out.

A direct measurement of the L-conversion coefficient of the 123.7-keV transition (as well as the K-conversion coefficients of the 215.8-, 372.8-, and 496.1-keV transitions) was made by measuring the internal and external conversion lines in the DFIC spectrometer (IEC method). The technique involved has been discussed elsewhere,[13] as has the experimental arrangement used in these measurements.[14] External conversion was accomplished with a rectangular uranium converter of dimensions 5 mm x 9 mm and of surface thickness 0.75 ± 0.02 mg/cm^2. The conversion coefficient is given by the following expression:

$$\alpha_i = \frac{(A_{in})_i}{(A_{ex})_j} \tau_j f_j k db$$

where α_i is the internal conversion coefficient of the ith shell or subshell, $(A_{in})_i$ the intensity of the internal conversion line from the ith shell or subshell, $(A_{ex})_j$ the intensity of the external photoelectric conversion line

from the jth shell of the converter, τ_j the photoelectric cross section for the jth shell, f_j the photoelectric angular distribution correction factor,* k the ratio of the external to internal source strengths (k = 1 here), d the thickness of the converter in mg/cm^2, and b a dimension factor. The relevant portions of the internal and external conversion spectra are shown in fig. 3.

For the 123.7-keV transition, we obtained a value $\alpha_L = 0.23 \pm 0.04$, which can be compared to theoretical L-conversion coefficients of 0.21 and 0.069 for an E2 and M1 transition, respectively.

The 55.0-, 78.6-, 92.3- and 156.9-keV Transitions

The establishment of the 55.0-keV transition as essentially pure E2 follows from the agreement between the experimental and theoretical L-subshell ratios, i.e., $L_I/L_{II}/L_{III}$ = 1/7.4/9.5 as compared to 1/6.2/7.8 and 1/0.077/0.019 for an E2 and M1 transition, respectively.

The 78.6-keV transition is assigned multipolarity M1 on the basis of the experimental ratio K/L = 8.7 [versus theoretical values of 8.4 (M1) and 1.8 (E2), respectively], and L-subshell ratios $L_I/L_{II}/L_{III}$ = 1/0.12/<0.06 [versus 1/0.075 / 0.0018 (M1) and 1/3.3/4.4 (E2)]. An E2 admixture of <2% cannot be completely ruled out.

The assignments of the 92.3- and 156.9-keV transitions as M1 follow from the fact that we did not definitely observe their L_{II} and L_{III} conversion lines. (For an E2 transition, all three L lines would be expected to have essentially the same intensity for a 156.9-keV transition, and nearly so for a 92.3-keV transition.)

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The 133.5-keV Transition

The K/L ratio (6.3) and L-subshell ratios ($L_I/L_{II}/L_{III}$ = 1/0.25/0.25) clearly indicate that the 133.5-keV transition is an M1 + E2 admixture (about 80% M1 + 20% E2).

The 215.8-, 372.8- and 496.1-keV Transitions

From the experimentally determined K-conversion coefficient, α_K = 0.093 ± 0.014, K/L ratio of >6.7, and L subshell ratio (L_I/L_{II} = 1/0.16), the 215.8-keV transition best fits an M1 or M1 + E2 admixture. It should be noted that the 246.3-keV K line is composite with the 215.8-keV L_{II} line, and on the basis of our intensities, could accommodate nearly the entire intensity assigned to the latter. This would have the effect of increasing both the K/L and L_I/L_{II} ratios, which would tend to favor the M1 assignment.

By the IEC method, we have determined the K-conversion coefficient of the 372.8-keV transition as α_K = 0.026 ± 0.006, which is to be compared to the theoretical values of 0.0185 and 0.0215 for an E2 and M1 transition, respectively. Although our measured value favors an M1 assignment, as previously mentioned, we have assumed the 372.8-keV transition to be 50% M1 + 50% E2 in the analysis.

The K-conversion coefficient of the 496.1-keV transition was determined as α_K = 0.012 ± 0.002 by the IEC method. Comparison of this value with the theoretical values of 0.0105 and 0.0082 for an M1 and E2 transition, respectively, indicates that the 496.1-keV transition is predominantly M1.

7. Half-lives of the 123.7- and 133.5-keV Levels

The half-life of the 123.7-keV state (see fig. 5) has been measured by Coleman[15] as 4.1 ± 0.5 ns, by Vartapetian et al.[16] as 4.0 ± 0.3 ns, by Bodenstedt et al.[8] as 3.77 ± 0.05 ns and by Nainan[17] as 4.15 ± 0.08 ns. In their measurements, Bodenstedt et al. found that the 500 - 124 keV delay curve consisted of

two components.[8] By observing the coincidence photon spectra at a delay of 55 ns where the contribution of the 3.77 ns cascade was negligible, they showed that the longer component was a measure of the half-life of the 133.5-keV state ($\tau_{1/2} = 13.3 \pm 0.5$ ns).

In order to check the results of Bodenstedt et al.,[8] we have remeasured the 500 - 124 keV delay curve. As shown in fig. 4, the curve consists of two components corresponding to half-lives of 3.49 ± 0.31 ns and 12.7 ± 1.0 ns, in good agreement with the data of Bodenstedt et al.

8. Decay Scheme

Energy and intensity sums have been used to construct the decay scheme of 11.5-d Ba^{131} as shown in fig. 5. Although Cork et al. had proposed a level at 78.6 keV, their data were not sufficient to definitely establish the order of the 55.0- and 78.6-keV transitions.[2] This uncertainty has been removed by the observance of the 137.1- and 294.0-keV transitions between the 78.6-keV level and the 215.8- and 372.8-keV levels, respectively. The level at 696.5 keV, first suggested by August et al.[6] on the basis of coincidences between photons of energies 216 and 500 keV (480.4 keV in this work), is verified by the detection of transitions leading from this level to the ground, 123.7- and 372.8-keV states. The level at 584.8 keV has not been previously proposed.

Table 4 shows the transition intensities in percent electron-capture decays as calculated for the decay scheme shown in fig. 5. Assuming an L/K capture ratio 0.12 (from Rose and Jackson)[18] and a fluorescence yield 0.867 (from Wapstra et al.),[19] we calculate the number of K X-rays (expected on the basis of the decay scheme of fig. 5) is equal within experimental error to the measured value given in table 4. Hence, there appears to be no capture to the first four states in Cs^{131}. That there was no capture to the ground and 123.7-keV states had been surmised by August et al. on the basis of intensity sums and coincidence measurements between K X-rays and 123.7-keV photons.[6]

Also shown in fig. 5 are the percent electron-capture branches and logft values for same. The logft values were calculated on the assumption of a total decay energy of 1164 keV.[20]

9. Discussion

The ground-state spin and parity of Cs^{131} is known to be 5/2+.[21] Since the levels in Cs^{131} (shown in fig. 5) are connected by even parity transitions, these states are assumed to have even parity. Furthermore, systematics of the ground-state spins of odd-A barium isotopes indicate that the ground state of Ba^{131} is 1/2 + or 3/2 +. This, together with the logft values determined in this work, implies that the levels in Cs^{131} which are populated by electron capture in the decay of Ba^{131} have spin values $\leq 5/2$.

Lindqvist and Karlsson[22] measured the angular correlation of the 496-124 keV cascade and obtained $A_2 = + 0.007 \pm 0.002$ and $A_4 = -0.002 \pm 0.004$. Haskins[7] determined the anisotropy of this cascade to be + 0.01 ± 0.02, in good agreement with the results of Lindqvist and Karlsson. Preliminary angular correlation measurements of the same cascade by Bodenstedt et al. indicated the 496 - 122 keV cascade to be isotopic and the anisotropy of the 488-133 keV cascade to be about 100%.[8] On the basis of their preliminary measurements, the latter authors suggested spin 1/2 + for the 123.7-keV level and 7/2 + for the 133.5-keV level. However, further measurements by Bodenstedt's group resulted in values for the 496 - 122 keV cascade of $A_2 = 0.0091 \pm 0.0006$ and $A_4 = 0.0004 \pm 0.0006$, in addition to values for the 912 - 122 keV cascade of $A_2 = -0.015 \pm 0.005$ and $A_4 = 0.00 \pm 0.01$.[23] Obviously, the latter results would exclude spin 1/2 for the 123.7-keV state. Before excluding such an assignment, however, a few comments concerning the aforementioned angular correlation measurements are in order. In their measurements on the 496 - 122 keV and 912 - 122 keV cascades, Bodenstedt's group has pointed out the possibility of interference from cascades

involving the 133-keV transition.[23] For the former cascade, one has to correct for the contribution from the 486.4-133.5 keV cascade. At the time, they were unaware of the transition between the 1046.5- and 133.5-keV levels as well as precise values for the energies of the transitions involved. Lindqvist and Karlsson[22] and Haskins,[7] did not consider effects from interfering cascades. Since the A_2 values determined in these measurements are small and their signs could be accounted for by cascades involving the 133.5-keV transition, it appears that one should not consider these data sufficient to definitely rule out spin 1/2+ for the 123.7-keV level. Our L-subshell ratios for the 123.7-keV transition are also incapable of resolving this problem.

As has been pointed out by Haskins[7] and the Nuclear Data Group,[1] energy systematics of the splitting between the 5/2+ and 7/2+ levels in the odd-A cesium isotopes predict a 7/2+ level at about 80 keV in Cs^{131}. The M1 character of the 78.6-keV transition would be consistent with such an assignment for the 78.6-keV level, and we tentatively assign it so. Should one measure the half-life of this level, a comparison with a similar case in Cs^{133} (where the splitting is about the same energy, but the 7/2+ level lies lower[1]) might shed additional light on this point. With this assignment it follows that the 133.5-keV level has spin and parity 3/2+, since it decays to the 78.6-keV level by an E2 transition, and to the ground state by an M1 + E2 admixed transition.

That the transitions from the 372.8-keV level to the 133.5-keV and ground states are partially M1, indicates the 372.8-keV level has spin and parity 3/2+ or 5/2+. The decay of the 215.8-keV level to the ground, 78.6- and 133.5-keV states restricts its spin to 3/2+ or 5/2+.

Although Bodenstedt's group[23] has also measured the angular correlations for the 245-370, 820-214, and 405-214 keV cascades, we have been unable to

to utilize these data to restrict further the spin assignments, without invoking assumptions as to the purity of the transitons involved. The number of spin combinations that would be consistent with the experimental data per se by allowing various admixtures, is too large to warrant a detailed discussion here.

The measured half-lives of the 123.7- and 133.5-keV levels permit a comparison of the absolute transition probabilities with those calculated by the Moszkowski single particle formula[24] (with a nuclear radius $r = 1.2 \times 10^{-13} \times A^{1/3}$ cm). These results are given in Table V. Here it is shown that the 55.0-keV E2 transition is enhanced by a factor of 46 over that expected for a single particle transition, and the E2 component of the 123.7-keV transition is similarly enhanced by about 65. The E2 component of the 133.5-keV transition, however, is nearly equal to the single particle estimate. The M1 components of the 123.7- and 133.5-keV transitions (assuming the former is composed of 8% M1) are seen to be retarded by factors of 5300 and 3600, respectively.

One possible interpretation of the foregoing results is that the ground state of Cs^{131} corresponds to the $d_{5/2}$ single particle level, and the 78.6-keV state to the $g_{7/2}$ level. The 123.7- and 133.5-keV states could then be collective states based upon the ground and 78.6-keV states, respectively. On this basis, one might expect that should the 78.6-keV transition contain an E2 admixture, its transition rate would be close to the single particle estimate. This is actually the case for the analogous transition in Cs^{133}.

From the shell model, the ground state of Ba^{131} is expected to be $s_{1/2}$ or $d_{3/2}$.[25] The assignment of $s_{1/2}$ for this state would readily explain the lack of electron capture to the first four states of Cs^{131}, since the transitions to the ground and 78.6-keV states would be second and third forbidden,

respectively, while those to the 123.7- and 133.5-keV states might be expected to be at least ℓ-forbidden. It should be noted, that such an $s_{1/2}$ assignment for the ground state of Ba^{131} would restrict the levels of Cs^{131} populated by electron capture to have spins 1/2 or 3/2.

In summary, we note that as a result of this work:

(1) A consistent decay scheme for 11.5-d Ba^{131} has been constructed which clarifies most of the known experimental data.

(2) Acceptance of the presently available experimental data per se does not yet allow definite spin assignments to all known levels in Cs^{131}.

(3) Our tentative spin assignment of 3/2+ to the 133.5-keV level and interpretation of the first four levels in Cs^{131} do not allow a comparison of these results with the work of Person and Rasmussen.[9] (The latter authors based their calculations on spins of 1/2+ and 7/2+ for the 123.7- and 133.5-keV levels, respectively.)

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Table I. Ba^{131} Conversion Electron Data.

Electron Energy (keV)	Conversion Shell	Transition Energy (keV)	Selected Transition Energy (keV)	Relative Electron Intensities[a]				Remarks
				180°[b] spect.	IF[c] spect.	DFIC[d] spect.	August[6]	
19.02	K	54.99	55.0					
49.34	L_I	55.05		2.3				
49.66	L_{II}	55.02		17.1	20.4	41.3		
50.02	L_{III}	55.03		21.9	25.6			
54.00	M_I	55.21			11.4			
54.86	N_I	55.09			4.9	14.4	?	
42.62*	K	78.60	78.6		51.0	55.7		
72.86	L_I	78.57	5.7					
73.35	L_{II}	78.71	0.7			6.4		
73.72	L_{III}	78.73	<0.3					
77.48	M_I	78.69						
78.42	N_I	78.56				2.06		
46.42*	K	82.39	82.4		1.83			
56.28*	K	92.26	92.3		26.8	28.9		
86.66	L_I	92.36						L_I line hidden by tail of K 123.7 in DF spectrometers
86.83	L_{II}	92.19					?	
87.56	L_{III}	92.57						Observation of L_{II} and L_{III} lines in PMS questionable
91.32	M_I	92.53				0.45		
87.73*	K	123.70	123.7		925	975		
117.90	L_I	123.61		82	91			
118.25	L_{II}	123.56		109	114	328	290	
118.62	L_{III}	123.64		137	123			
122.58	M_I	123.79			57.1			
123.45	N_I	123.68			10.8	85.1		

Table I. (Cont'd)

Electron Energy (keV)	Conversion Shell	Transition Energy (keV)	Selected Transition Energy (keV)	Relative Electron Intensities[a] 180°[b] spect.	IF[c] spect.	DFIC[d] spect.	August[6]	Remarks
97.51*	K	133.48	133.5		43.5	43	25	
127.83*	L_I	133.54		4.6				
128.17*	L_{II}	133.53		1.1		6.82		
128.36	L_{III}	133.38		1.1				
132 23	M_I	133.43				2.18		
101.16*	K	137.13	137.1		1.18	0.85		
120.94	K	156.91	156.9					K line hidden by L_{III} and M 123.7 in DFIC spectrometer
151.17	L_I	156.88				0.30	?	
179.78*	K	215.75	215.8		100	100	100	
209.81	L_I	215.53		12.9		15.0		Composite with K 246.3 in DF spectrometers
210.34	L_{II}	215.70		2.1				
214.43	M_I	215.64						
215.40	N_I	215.63				2.98		
203.19	K	239.16	239.2			9.16	10	
233.44	L_I	239.15				1.11	2	Appeared to be broad in PMS
237.54	M_I	238.75				0.55		
210.34	K	246.31	246.3					Composite with L_{II} 215.8
240.59	L_I	246.3				0.53		
244.93	M_I	246.1						Composite with L and M 248.8 in DFIC spectrometer
212.87	K	248.84	248.8			8.82		
243.14	L_I	248.85				1.23	2	
247.69	M_I	248.82				0.37		

UCRL-10582

Table I. (Cont'd)

Electron Energy (keV)	Conversion Shell	Transition Energy (keV)	Selected Transition Energy (keV)	Relative Electron Intensities[a]				Remarks
				180°[b] spect.	IF[c] spect.	DFIC[d] spect.	August[6]	
258.00	K	293.97	294.0			0.34		
287.9	K	323.9	323.9	≈ 0.06				
314.3	K	350.3	350.3	0.12				
336.80	K	372.77	372.8			15.5	17.2	
367.31	L	372.9				3.08		Composite with K 403.9
371.51	M	372.7				0.56		
367.31	K	403.3	403.9					Composite with L 372.8
398.17	L	403.9				0.14		
390.7	K	426.7	426.7	0.06				
416.02	K	452.0	452.0	0.3				
425.1	K	461.1	461.1	0.05				
444.38	K	480.35	480.4			0.32		
474.67	L	480.38				0.04		
450.42	K	486.39	486.4			1.04		
480.41	L	486.12				0.11		
460.17	K	496.14	496.1			25.9	30.1	
490.29	L	495.9				3.56		
494.76	M	496.0				0.72		
537.1	K	573.1	573.1			0.057		

Table I. (Cont'd)

Electron Energy (keV)	Conversion Shell	Transition Energy (keV)	Selected Transition Energy (keV)	Relative Electron Intensities[a] 180°[b] spect.	IF[c] spect.	DFIC[d] spect.	August[6]	Remarks
548.79	K	584.76	584.8			0.42	0.56	
580.12	L	585.7				0.06		
583.58	M	584.8						Composite with K 619.6
583.58	K	619.55	619.6			0.32	0.47	Composite with M 584.8
614.32	L	619.9		0.05		0.03		
638.2	K	674.2	674.2	0.05				
660.6	K	696.5	696.5	0.04				
794.9	K	830.9	830.9	0.04		0.04	0.04	
878.1	K	914.1	914.1	$\lesssim$ 0.01				
886.9	K	922.9	922.9			0.09	0.08	
917.2	L	922.9				0.01		
1010.5	K	1046.5	1046.5			0.12	0.14	
1041.2	L	1047.2				0.01		

*Electron energy measured in IF spectrometer.

[a]We estimate the relative precision of these intensities to be better than ± 20%.

[b]Intensities determined in PM spectrometers have been normalized to values obtained with the DFIC spectrometer.

[c]Intensities normalized to DFIC values at L 123.7.

[d]Intensities arbitrarily normalized to 100 for K 215.8.

Table II. Relative Photon Intensities in the Decay of Ba^{131}.

Photon Energy[a] (keV)	Relative Intensity[b] This Work	Relative Intensity[b] Campbell[6]
K X-ray	4739	
123.7		
133.5	1660	2080
137.1		
156.9	51.4[c]	105
215.8	1120	1570
239.2		
246.3	356	595
248.8		
372.8	775	1030
403.8	121	154
480.4		
486.4	2850	2850
496.1		
573.1	110	101
584.8		
619.6	83[d]	100

Table II (Cont'd)

Photon Energy[a] (keV)	Relative Intensity[b] This Work	Relative Intensity[b] Campbell[6]
674.2 696.5	52	24
830.9	15	22
922.9	46.3	54
1046.5	80	87

[a] When applicable, the photon energies are those determined in the conversion electron measurements.

[b] These intensities are normalized in the manner adopted in table IV.

[c] This intensity has been corrected for solid angle addition of 123.7-keV photons and K X-rays ($\approx$ 12%).

[d] This intensity has been corrected for solid angle addition of 496.1- and 123.7- keV photons ($\approx$ 10%).

Table III. Summary of Data Pertaining to Multipole Order Assignments of Transitions in the Decay of Ba^{131}.

Transition Energy (keV)	K/L	$L_I/L_{II}/L_{III}$	α_K	Multipole Order
55.0		1/7.4/9.5[a,b]		E2
78.6	8.7 ± 0.9	1/0.12 < 0.06[a]		M1 or 98% M1 + < 2% E2
92.3		1/.../...[a]		M1
123.7	3.0 ± 0.2	1/2.25/1.35[b]	0.23 ± 0.04[c,d]	E2 or E2 + < 10% M1
133.5	6.3 ± 0.7	1/0.25/0.25[a,b]		80% M1 + 20% E2
156.9		1/.../...[a]	0.006[c]	M1
215.8	>6.7	1/0.16/...[a,e]	0.093 ± 0.010[d]	M1 or M1 + E2
239.2	8.3 ± 1.2		0.063	M1 or M1 + E2
248.8	7.2 ± 1.5		0.062	E2 or M1 + E2
372.8	>5.0[f]		0.026 ± 0.006[d]	M1 or M1 + E2
403.9			0.0012[c]	
480.4	7.5 ± 1.9		0.0097	M1 + E2
486.4	9.1 ± 1.8		0.0096	M1 or M1 + E2
496.1	7.3 ± 0.8		0.012 ± 0.002[d]	M1 or M1 + E2
573.1			0.0043	
584.8	7.2 ± 1.5		0.0042	E2
619.5	10 ± 3[g]		0.0039	E2 or M1 + E2
674.2			0.0017	

Table III. (Cont'd)

Transition Energy (keV)	K/L	$L_I/L_{II}/L_{III}$	α_K	Multipole-Order
696.5			0.0017	
830.9			0.0027	M1 + E2
922.9	9 ± 3[g]		0.0020	M1 + E2
1046.5	8.4 ± 1.6[g]		0.0015	M1 + E2

[a] Determined visually from photographic plates of permanent magnet spectrometers.

[b] Measured with iron free spectrometer.

[c] This value is for the L conversion coefficient.

[d] Measured by the internal-external conversion method (IEC).

[e] The K 246.3 line is composite with the L 215.8 line, and its contribution to the latter has not been removed, hence, the low K/L ratio. (see text for further comment.)

[f] The K 403.9 line is composite with the L 372.8 line, and its contribution to the latter has not been removed, hence, the low K/L ratio.

[g] For these transitions the ratio is K/LM.

Table IV. Total Transition Intensities in the Decay of Ba^{131}.

Transition Energy (keV)	Relative Electron Intensity (arbitrary units)		Relative Photon Intensity		Total Transition Intensity (% EC decays)
	K	ΣL,M...			
K-X	(194)	100		4730	
55.0	(34.2)[a]	55.7		(5.4)[a]	1.68
78.6	55.7	8.5		(37)[b]	1.97
82.4	1.8			(1)[c]	0.05
92.3	27.8	> 0.45		(27.8)[d]	1.0
123.7	975	406	1550[e]		52.0
133.5	43	9.0	116[f]	1660	2.98
137.1	1.0		2.2[g]		0.06
156.9	(2.6)[h]	0.3		51.4	0.96
215.8	100	18.0		1120	21.9
239.2	9.2	1.66	146[j]		2.78
246.3	(3.5)[i]	0.53	69	356	1.3
248.8	8.8	1.76	141		2.69
294.0	0.34			(8.5)[k]	0.16
323.9	0.06			(2.3)[c]	0.04
350.3	0.12			(5.2)[c]	0.09
372.8	15.5	3.6		[775][l]	14.1
403.9	(1.95)[c]	0.14		121	2.18
426.7	0.06			(4.4)[c]	0.08
452.0	0.3			(25)[c]	0.45
461.1	0.05			(4.5)[c]	0.08

Table IV. (Cont'd)

Transition Energy (keV)	Relative Electron Intensity (arbitrary units) K	Relative Electron Intensity (arbitrary units) ΣL,M...	Relative Photon Intensity		Total Transition Intensity (% EC decays)
480.4	0.32	0.04	33 [m]		0.59
486.4	1.04	0.11	109	2850	1.95
496.1	25.9	4.28	2710		48.6
573.1	0.06		14 [m]	110	0.25
584.8	0.42	0.06	96		1.7
619.6	0.32	0.03		83	1.48
674.2	0.05		29 [m]	52	.52
696.5	0.04		23		.41
830.9	0.04			15	.27
914.1	≈ 0.005		46	46.2	
922.9	0.09	0.009			.82
1046.5	0.12	0.014		80	1.42

[a] Calculated assuming theoretical K/L ratio (0.834) and L conversion coefficnent for an E2 transition (see Table III).

[b] Calculated assuming theoretical K conversion coefficient for an M1 transition (see Table III).

[c] Calculated assuming theoretical K conversion coefficient for a 50% M1 + 50% E2 transition.

[d] Calculated assuming theoretical K conversion coefficient for an M1 transition (see Table III).

[e] Calculated assuming theoretical K conversion coefficient for an E2 transition (see Table III).

[f] Calculated assuming theoretical K conversion coefficient for a 80% M1 + 20% E2 transition (see Table III).

[g] Calculated assuming theoretical K conversion coefficient for an E2 transition.

[h] Calculated assuming theoretical K/L ratio for an M1 transition (see table III).

Table IV. (Cont'd)

[i] Calculated assuming theoretical K/L ratio for a 50% M1 + 50% E2 transition.

[j] Photon intensity distributed on the basis of K and L electron intensities of the 239.2-, 246.3- and 248.8- keV conversion lines.

[k] Calculated assuming theoretical K conversion coefficient, $\alpha_K = 0.04$.

[l] Photon relative intensity scale normalized to the theoretical 50% M1 + 50% E2 conversion coefficient of the 372.8-keV transition, $\alpha_K = 0.02$.

[m] Photon intensity distributed according to K conversion electron intensities.

Table V. Transition Probabilities

Transition (keV)	Theoretical[a] (sec^{-1})	Experimental (sec^{-1})	Expt./Theory
55.0 - E2	2.4×10^{4}	1.1×10^{6}	46
123.7 - E2	1.4×10^{6}	9.5×10^{7}	68
123.7 - 92% E2	1.4×10^{6}	8.8×10^{7}	63
- 8% M1	5.3×10^{10}	9.8×10^{6}	1.9×10^{-4}
133.5 - 20% E2	2.1×10^{6}	3.9×10^{6}	1.9
- 80% M1	6.7×10^{10}	1.9×10^{7}	2.8×10^{-4}

[a]The statistical factor has been set equal to one.

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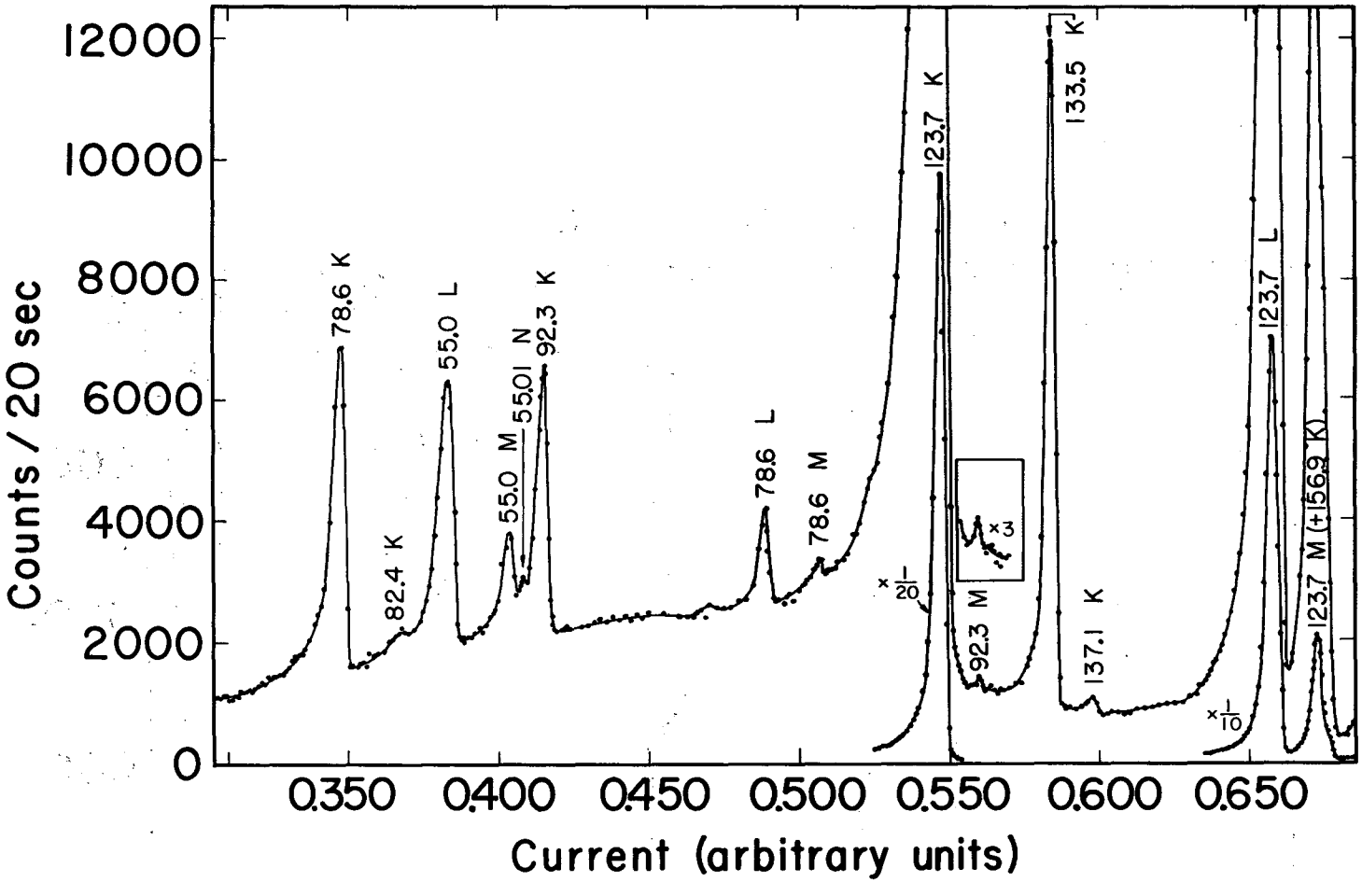

Fig. 1. Internal conversion spectrum of Ba^{131} taken with an iron-core, double focusing spectrometer (DFIC).

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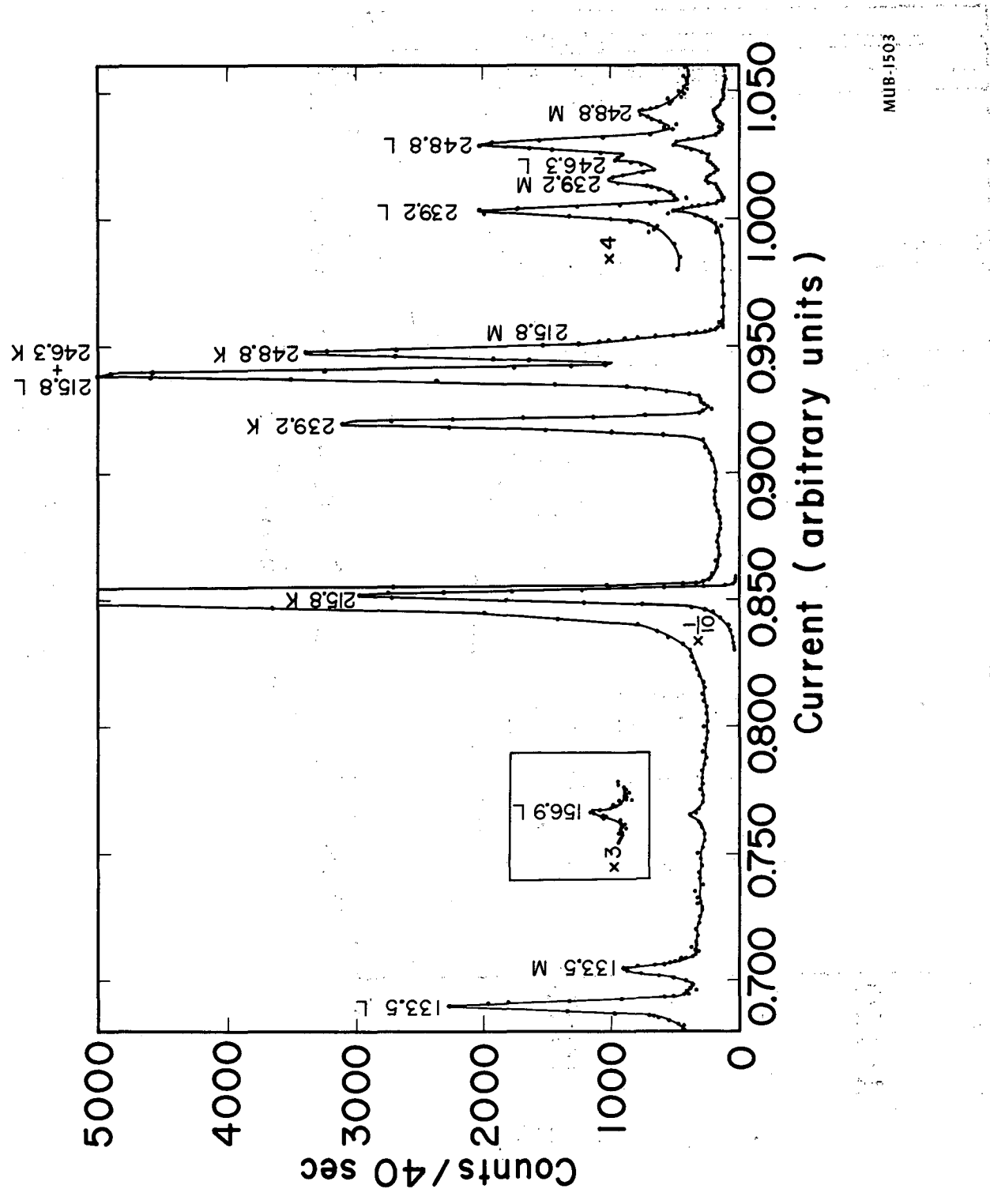

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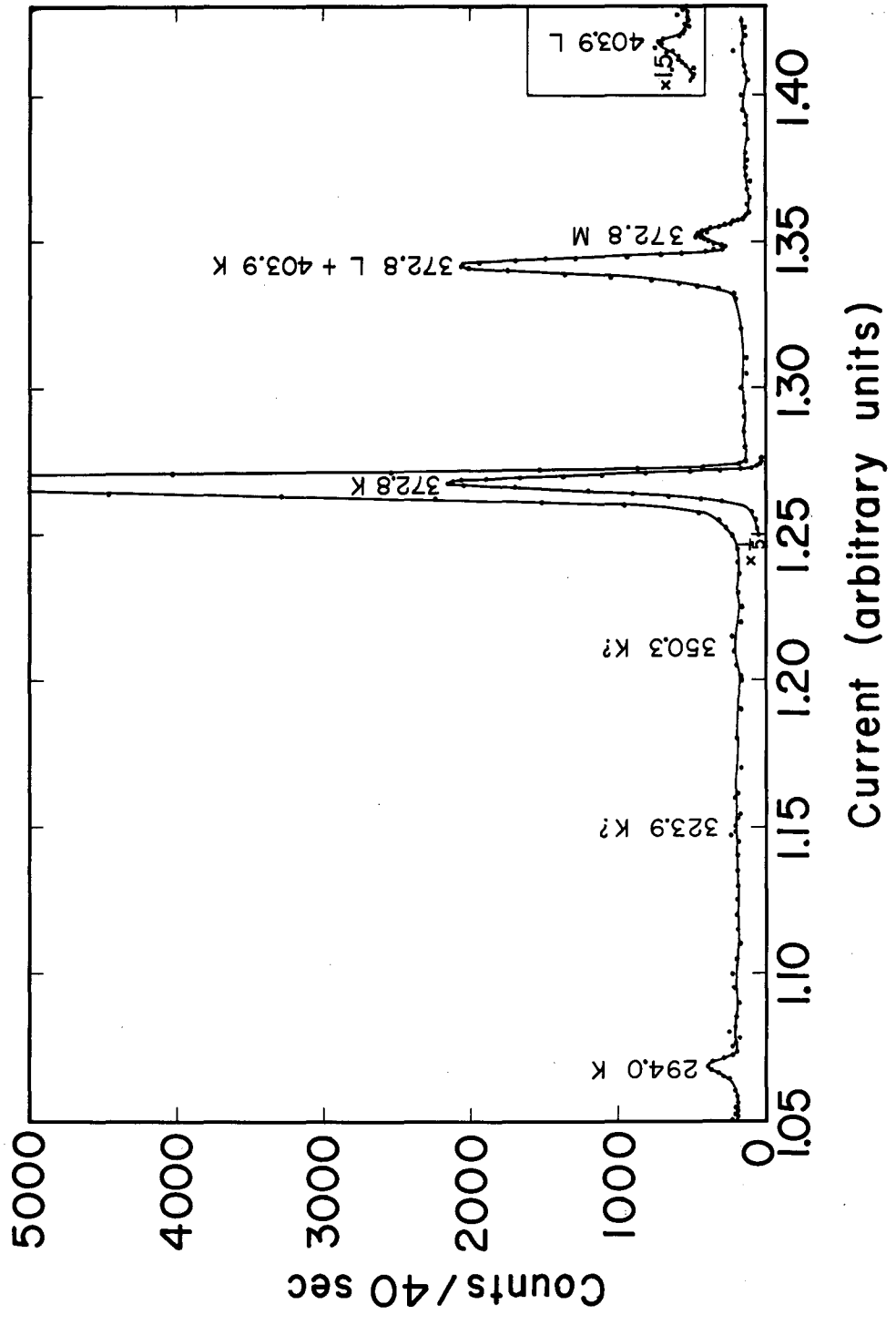

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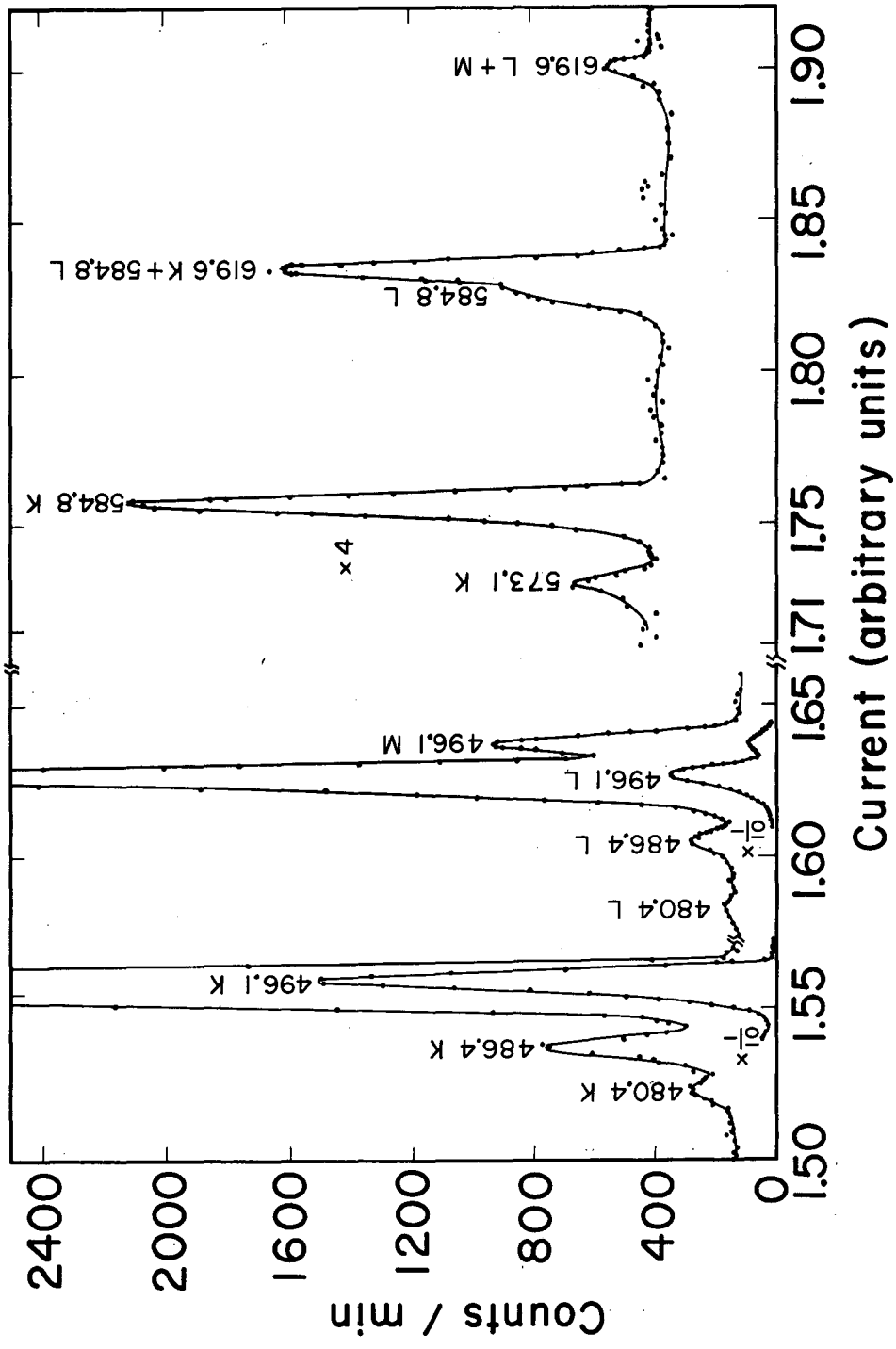

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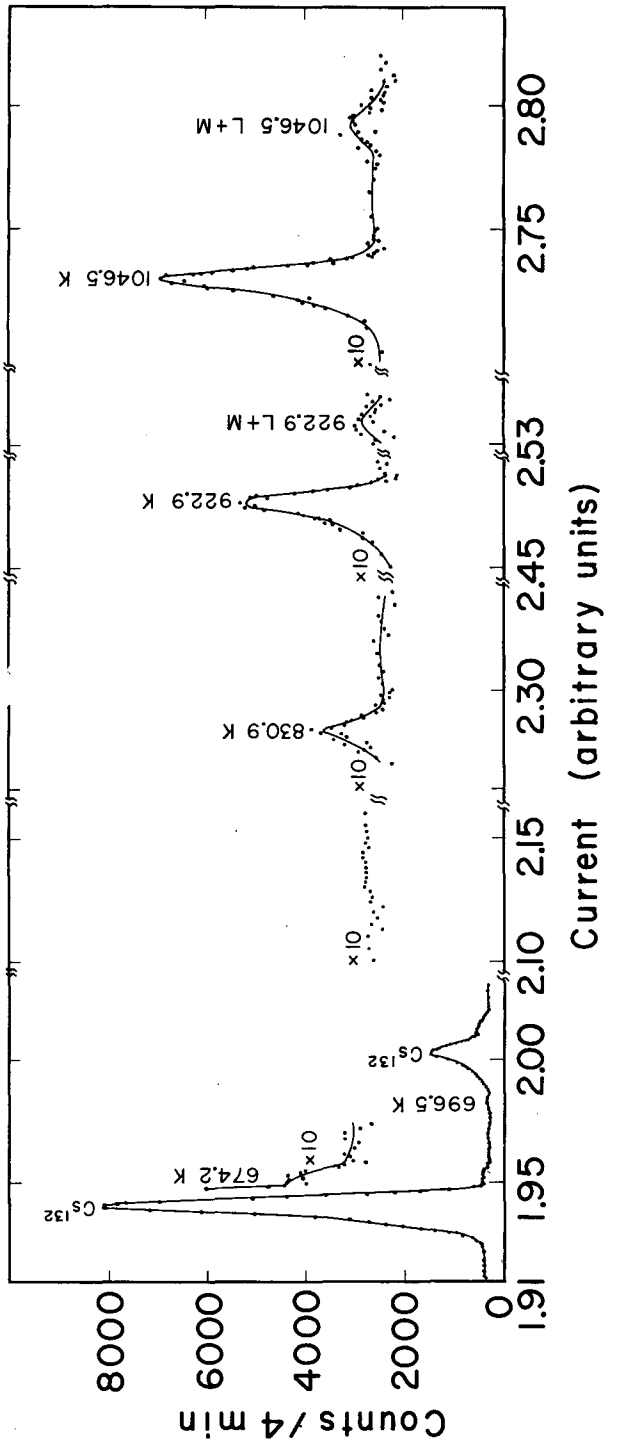
Fig. 1 continued.



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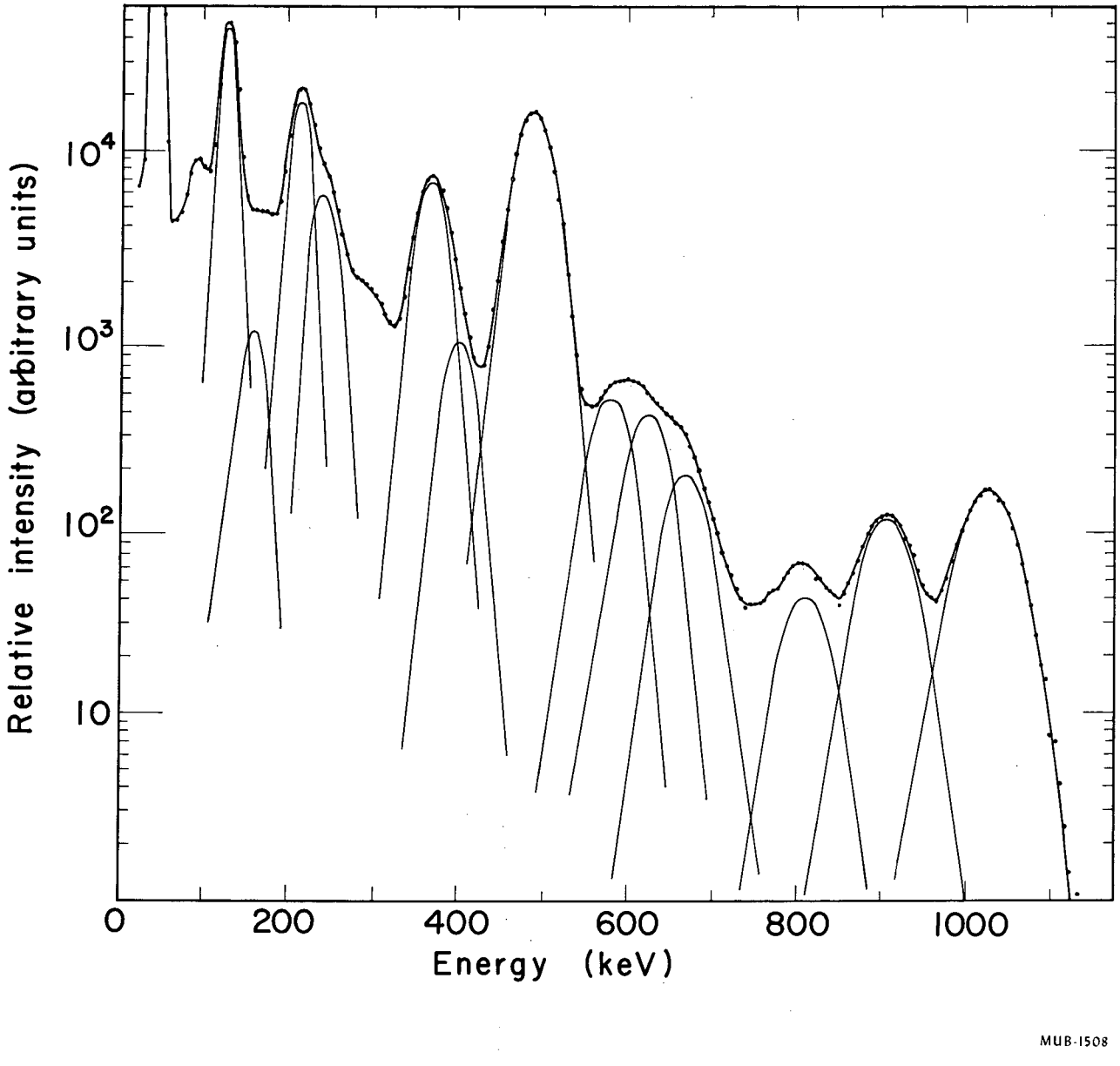

Fig. 2. Singles photon spectrum of Ba^{131} taken with a 7.6cm x 7.6cm NaI(Tl) crystal at a source to crystal distance of 20cm.

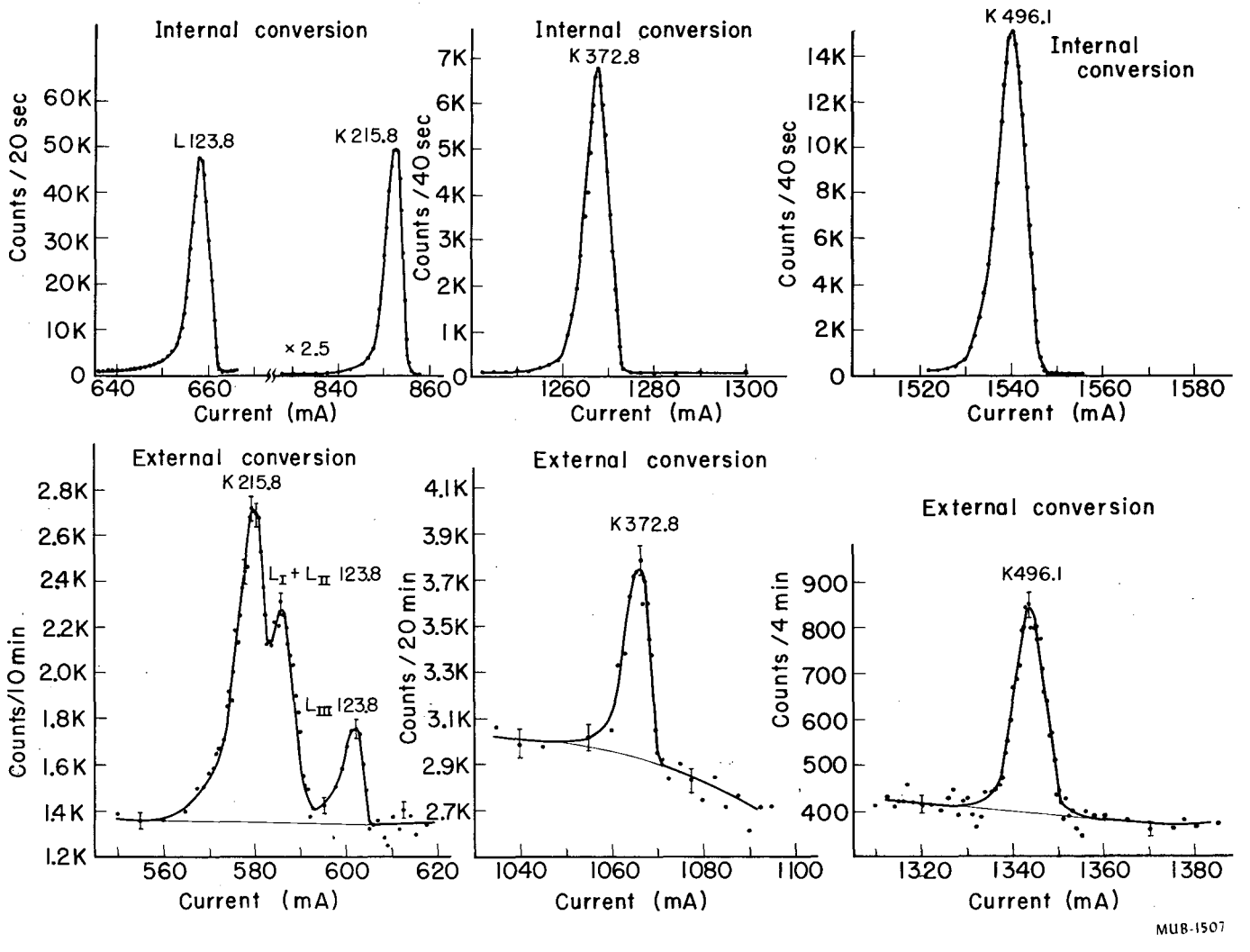

Fig. 3. Internal and external conversion electron spectra for the 123.7-, 215.8- and 496.1-keV transitions.

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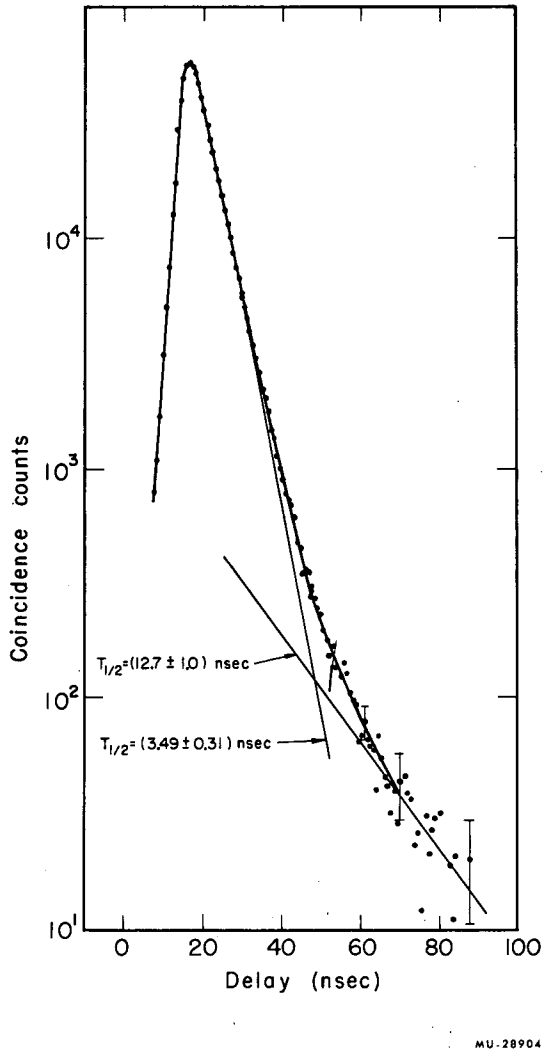

Fig. 4. Delayed coincidence curve for the cascades with transition energies in the ranges 500 ± 40 keV and 125 ± 15 keV. Chance coincidences have been subtracted.

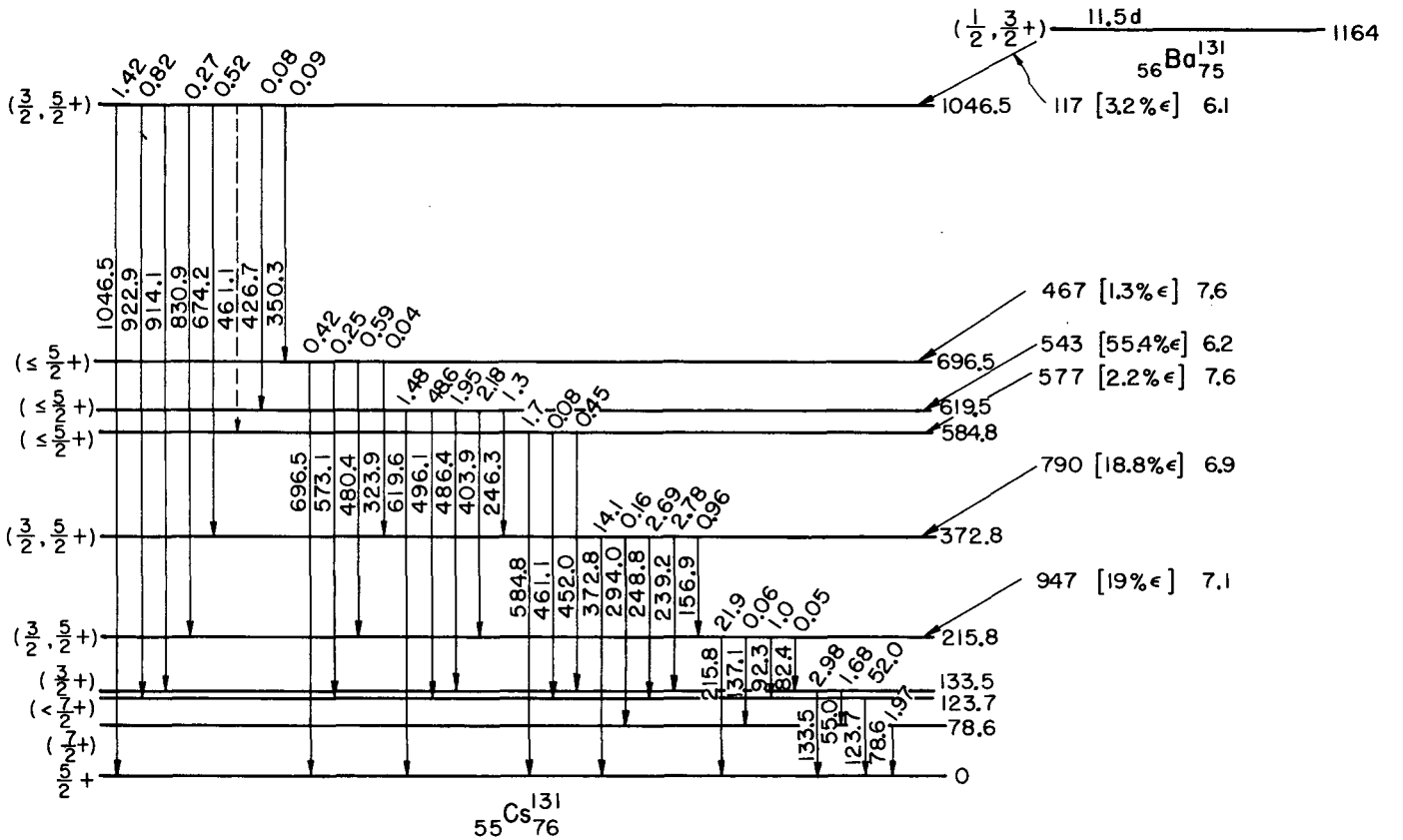

Fig. 5. Tentative decay scheme for 11.5-d Ba^{131}. All energies are given in keV, the percent electron capture within the brackets, and the log ft values to the right of the percent branchings.