Level scheme of ^{140}Cs

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Biparametric coincidence techniques using low energy photon spectrometer detectors have been used in order to determine energies, intensities, conversion coefficients, and placements of transitions in the level scheme here proposed for ^{140}Cs. A new 9.4 keV ($I_\gamma < 0.7\%$) γ ray has been found and a doublet character for 38 keV [38.34 keV ($I_\gamma = 0.9 \pm 0.2$ %) and 38.33 keV ($I_\gamma = 0.1 \pm 0.1$ %)] has been established. Ten internal conversion coefficients were measured; three of them, as well as six additional K/L relations, have not been reported previously. Spin and parity assignments were made for 25 levels, based on our assigned multipolarities and log*ft* values.

[RADIOACTIVITY ^{140}Xe from ^{235}U(n,f); measured E_γ, I_γ, γ-γ coin, ICC (for low-energy γ); deduced multipolarities, levels, J, π, logft. Mass-separated ^{140}Xe.]

I. INTRODUCTION

The study of odd-odd nuclei has been the subject of much work in recent years. These studies present two main difficulties: On the one hand, the theoretical interpretation is not as clearly formulated as in the case of even-even or even-odd nuclei, and on the other, their decays produce a great number of low-energy gamma rays, not always easily detected.

The first important work on the decay of ^{140}Xe was made by Schick *et al.*[1] In this work, a level scheme based on biparametric Ge(Li)-Ge(Li) coincidences was proposed even though seventeen inconsistent coincidences were shown. The same group in Ref. 2 increased the previous information with additional low-energy gamma rays and internal conversion coefficient (ICC) measurements for energies between 80 and 810 keV. However, the fact that no ICC values were available below 80 keV introduces great uncertainties in the intensity balance of the low-energy levels and their log*ft* calculations.

Angular correlation measurements[3] were also reported. The ground-state spin of ^{140}Cs (Ref. 4) and the Q_β values[5] have been also measured. Recently Peker[6] published a complete compilation about ^{140}Cs.

In the present work biparametric coincidence techniques using low energy photon spectrometer (LEPS) detectors have been applied in order to obtain energies, intensities, conversion coefficients, and the placements in the corresponding level scheme of the low-energy transitions of ^{140}Cs. Briefly, our new results consist of: a previously unreported low-energy gamma ray of 9.4 keV; establishment of the doublet character of the 38-keV transition and the placement in the level scheme of each member of the doublet; and the measurement of ten internal conversion coefficients, three of them previously unreported. Besides, K/L relations were determined for six cases. We attemped to get a good knowledge of the low-energy region of ^{140}Cs in order to obtain reliable log*ft* values, particularly for the high-energy region where the beta-decay mode provides valuable information about the level structure.

II. EXPERIMENTAL PROCEDURE

The samples used in these measurements were produced in the Buenos Aires on-line facility, which was described in detail in Ref. 7. Briefly, an uranyl-stearate target containing 10 g of ^{235}U is placed in a thermal neutron flux. The rare gases produced in the ^{235}U fission are fed into the ion source of an electromagnetic separator and the mass of interest is received on an appropiate collector.

Singles gamma-ray measurements were made using a Ge(Li) detector (with 2.8-keV resolution for the ^{60}Co gamma rays) above 80 keV, a LEPS Ge(Li) detector (with 2-keV resolution for the ^{137}Cs gamma ray) from 10 to 120 keV, and an x-ray Si(Li) detector (with 290-eV resolution for ^{59}Fe x-ray lines) below 50 keV. The relative efficiency calibration for the 2.8-keV detector was made as described in Ref. 8. For the LEPS detector and the x-ray detector, the efficiency calibration was made as described in Ref. 9.

The gamma-gamma coincidence measurements were performed with the above mentioned Ge(Li) detector and another 3-keV resolution Ge(Li) detector. The energy range from 10 to 120 keV was covered with the LEPS and one of the Ge(Li) detectors in coincidence. The signals were processed by two 4096-channel analog-to-digital converters and both generated addresses stored on a magnetic tape buffer. The data on this tape were later read back into the computer using a digital window placed at the position of the desired gating peak and an additional window near this peak to automatically subtract coincidences due to the Compton background. Singles spectra were taken simultaneously with the coincidence spectra. The coincidence circuit used was of the fast-slow type with $2\tau = 150$ ns in both energy ranges. The experimental setup for internal conversion coefficient determinations [normalized conversion peak to gamma peak (NPG) method] and its calibration have been described in detail in Ref. 9.

III. EXPERIMENTAL RESULTS

A. Singles low-energy gamma-ray spectra, gamma-gamma coincidences, and ground-state beta-feeding measurements

The low-energy gamma-ray intensities were determined using the LEPS detector described above. A typical spectrum is shown in Fig. 1(b) and the results obtained are presented in Table I. A reasonable overall agreement with previous works[1,2] was obtained. However, the intensities of the 45- and 84-keV rays shown in Ref. 1 seem to be overestimated, possibly due to x-ray or backscattering contributions.

The gamma-gamma coincidence results are summarized in Table II. Our LEPS-Ge(Li) coincidences allowed us to improve the previous level scheme for energies below 120 keV; as in Ref. 1 many low-energy transitions were placed by sum relations. Based on our measurements we postulate the existence of a gamma-ray transition of 9.4 keV, which explains the gamma-gamma coincidence pairs at 38-1177, 89-1177, 103-510 (pointed out as "not consistent" in Ref. 1), 103-1315, 510-38, and 1315-103 keV. From the singles spectrum we obtained an upper limit of 0.7% for the gamma intensity of the 9.4-keV gamma transition.

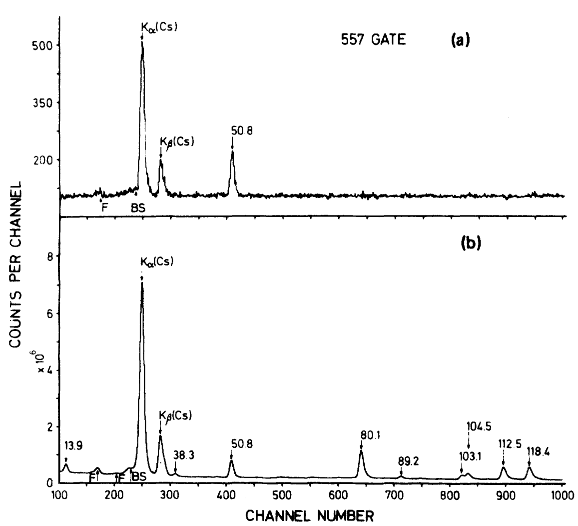

FIG. 1. (a) Coincidence spectrum observed with a LEPS detector in the decay of ^{140}Cs gated with a 557-keV transition from a Ge(Li) detector. Only the 50-keV transition and its x rays are observed. (b) Low-energy gamma-ray spectrum measured with a LEPS detector observed in the ^{140}Cs decay. Some important peaks are labeled by energy.

The 80-176 and 80-1309 keV coincidences suggest that a 38-keV transition exists between the 118.45- and 80.12-keV levels as postulated in Ref. 1 based on an energy relation. However, the set of coincidences 38-519, 38-1315, 38-1177, 50-1315, 510-38, 519-38, 1315-38, and 1315-50 keV implies that a new 38-keV transition exists between the 103.10- and 64.16-keV levels (see Sec. IV).

Seventeen gamma-gamma coincidence results in Ref. 1 were singled out by those authors as not consistent with their level scheme. From Table II of Ref. 1 we also found as being not consistent the following coincidences: 112-104, 118-112, and 118-390 keV. Both sets of coincidence results were not found at all in our measurements. We also observed that in the level scheme of Ref. 1 the transitions 786 and 1077 keV are marked with open circles although they appear neither in Table II of that reference nor in our measurements; therefore they were not taken into account in constructing our coincidence level scheme. Briefly, in this work, we remeasured the coincidences shown in Table II of Ref. 1, measured coincidences with six previously unreported gamma-ray gates of 14, 38, 48, 89, 120, and 215 keV, improved the existent data, and clarified previous inconsistencies between the measured data and the proposed level scheme.

To determine the ground-state beta feeding to ^{140}Cs we followed the same procedure as in Ref. 10. The transitions considered were the 557- and 622-keV gamma rays belonging to the ^{140}Cs decay and following the ^{140}Xe half-life (13.6 s), and the 602-keV gamma ray for ^{140}Ba (^{140}Cs half-life, 63.8 s). Assuming a zero beta feeding to the ^{140}Cs ground state, a $(40\pm4)\%$ beta feeding for the ^{140}Ba ground state is obtained. This value is about three times greater than that previously determined in Ref. 11. However, the logft and logf_1t of the ^{140}Ba levels do not change substantially. Schussler *et al.*[11] do not mention the steps followed in their work to get their value. With our data we establish that the 805.5-keV gamma-ray transition represents $(20\pm2)\%$ of the β^- decays from ^{140}Xe to ^{140}Cs.

B. Internal conversion measurements

Our results are summarized in Table I, and a typical electron spectrum is shown in Fig. 2. The

TABLE I. Low-energy γ and e^- results.

Transition energy [a]	γ-ray intensity [b]	Measured conversion coefficient	Method [c]	Assgined multipolarity	Transition intensity [d]
9.42 ± 0.03 [e]	<0.7 [f]				25 ± 12 [b]
13.93 ± 0.05	4.4 ± 0.4	α_L < 36	XPG	$M1$	205 ± 20
38.34 ± 0.03 [e]	0.9 ± 0.2 [f]	α_K = 12.0 ± 2.5	XPGC	$M1(E2)$	12.7 ± 3.4 [f]
38.33 ± 0.03 [e]	0.1 ± 0.1 [g]				2.9 ± 1.5 [f]
45.89 ± 0.10	0.08 ± 0.03				0.16 ± 0.07 [h]
47.75 ± 0.03	0.24 ± 0.04				4.8 ± 2.4
50.82 ± 0.03	8.3 ± 0.5	α_K = 6.0 ± 1.1	XPGC	$M1(E2)$	122 ± 32
80.12 ± 0.03	22.0 ± 1.5	α_K = 1.8 ± 0.5 $K/L+M$ = 0.30 ± 0.25	XPGC NPG	$M1$-$E2$	69 ± 26
84.50 ± 0.02	0.11 ± 0.02				0.28 ± 0.14 [h]
89.17 ± 0.03	1.9 ± 0.1				4.8 ± 2.0 [h]
93.64 ± 0.05	0.50 ± 0.06				1.2 ± 0.6 [h]
99.56 ± 0.10	0.17 ± 0.05				0.3 ± 0.1 [h]
103.09 ± 0.03	4.8 ± 0.8	α_K = 0.66 ± 0.10 K/L = 3.2 ± 0.6 (103.09 + 104.52)	NPG	$M1$(25% < $E2$ < 60%)	8.0 ± 1.5
104.52 ± 0.03	6.4 ± 0.8				10.6 ± 1.7
108.95 ± 0.05	0.25 ± 0.12				0.4 ± 0.2 [h]
112.53 ± 0.03	18.5 ± 2.5	α_K = 0.70 ± 0.10 K/L = 12.0 ± 7	NPG	$M1$(<45% $E2$)	31.5 ± 4.7
118.44 ± 0.03	22.4 ± 2.5	α_K = 0.67 ± 0.10 K/L = 13.0 ± 7	NPG	$M1(E2)$	37.3 ± 5.0
167.26 ± 0.15	6.2 ± 0.6	α_K = 0.17 ± 0.03 K/L = 3.2 ± 0.6	NPG	$E2$(~25% $M1$)	7.2 ± 1.1
196.2 ± 0.2	1.10 ± 0.07	α_K = 0.10 ± 0.03		$M1(E2)$	1.2 ± 0.3
198.1 ± 0.2	2.80 ± 0.20				3.1 ± 0.4 [h]
212.00 ± 0.10	11.5 ± 1.3	α_K = 0.14 ± 0.03 K/L = 3.8 ± 0.8	NPG	$M1$(<29% $E2$)	13.2 ± 2.6

[a] Energies were taken from Ref. 1 except those labeled with e.

[b] The error stated for the 805.52-keV gamma ray intensity normalized to 100 has been included in the errors of the other intensities.

[c] XPG: x-ray peak to gamma-ray peak method in singles measurements. XPGC: Same method as above but in coincidence measurements. NPG: normalized conversion-peak-to-gamma-peak method. The ω_K and ω_L values were taken from W. Bambynek, B. Crasemann, R. W. Fink, H. V. Freund, H. Mark, C. D. Swift, R. E. Price, and P. Venwgopala Rao, Rev. Mod. Phys. 44, 716 (1972).

[d] Transition intensities were calculated assuming the assigned multipolarities.

[e] Energy calculated through the level scheme.

[f] Intensity obtained from quantitative coincidence results.

[g] This intensity was calculated taking into account the total intensity of 38.34 + 38.33 keV gamma rays and assuming $M1$-$E2$ multipolarity.

[h] Assuming $M1$-$E2$ multipolarity.

data analysis was made using the ANPIK program[12] as in Ref. 10. Above 80 keV the conversion coefficient determination was made through the NPG method and our results are in reasonable agreement with those of Ref. 2 except for the 112-keV gamma ray. For this transition we secure a $M1$ multipolarity component instead of the predominant $E2$ multipolarity assigned by Adams *et al.*,[2] based on our 12±7 measured K/L ratio. Theoretical K/L ratios are 7.7 and 2.83 for $M1$ and $E2$, respectively.

Below 80 keV we used the x-ray peak to gamma-ray peak (XPG) method applied to spectra taken in coincidence and the results are also summarized in Table I. In this way, both the gamma-ray peak of interest and its x rays are obtained. For example, in Fig. 1(a) we show the spectrum used to obtain the 50-keV transition conversion coefficient measured in coincidence with the 557-keV gamma ray. To determine the conversion coefficient we also used the 167- and 390-keV gated coincidence spectra.

The conversion coefficient of the 38.34-keV transition (between the 103.10- and 64.76-keV levels) was determined using the gate of 519 keV. The contributions to the x rays coming from the other 38.33-keV transition (placed between the 118.45- and 80.12-keV levels) and from the 50-keV

TABLE II. γ-γ coincidence results (transition energies in keV).

Gate	Definite	Doubtful
14	557	
38	519, 806, (1309-1315)	1177
48		806
51	167, 196, (227-283), 374, 390, 462, 557, (734-736), 806, (1309-1315)	483, 519, 989
80	215, 1209, 1309, 1348	842
85	196	277, 805
89	(515-519), 806, (1309-1315)	1177
94		925
103	519, 806, 1315	510
105	396, 429, (653-656), 880, (1309-1315)	176, 806
113	182, 232, 390, 510, 806, 1177, 1315	
118	176, 320, 396, 429, 462, (653-656), 880 913, 1309	503, 806, (862-864)
120		806
167	14, 51, 390, 806	
176		80, 118
182	113	51, 103
196	51, 277	
212	291, 441, 925	410, 806
215	80	672
277	159, 196, 331, 806	212
281		672, 1133
291	(212-215)	198, 281
331	277, 806	
374	51, 989	
390	51, 120, 167, 806	113
396	104, 118	
429	104, 118	880
439	989	
441	212	198
462	(103-105), 118, 952	
510	112	38, 806
515		913
519	38, 51, 89, 103, 806	
548	880	
557	51, 806	
608	806	
622	806	
653	105, 118, 656, 774	
656	118, 653	105
774	653	
806	51, 103, 113, 167, 390, 519, 557, 608, 622	38, 89, 105, 118, 212, 510
880	51, 118, 429, 548	105, 331
925	212	
989	438	51
1177	112	103
1209	80	
1309	105, 118	
1315	51, 103, 113	38, 89

transition were carefully discounted. For the former case it was necessary to use additional information coming from the level scheme in order to obtain, by means of a quantitative coincidence analysis, the 38.33-keV transition intensity. For the latter, $M1$ multipolarity was assumed. The energies of both transitions were adopted values resulting from fitted sum relations in our proposed level scheme (see Sec. IV). To determine the conversion coefficient of the 80-keV transition, the gates of 215 and 1209 keV were used.

The determination of the 14-keV transition conversion coefficient was made by the XPG method in singles spectra. It was measured with the Si(Li)

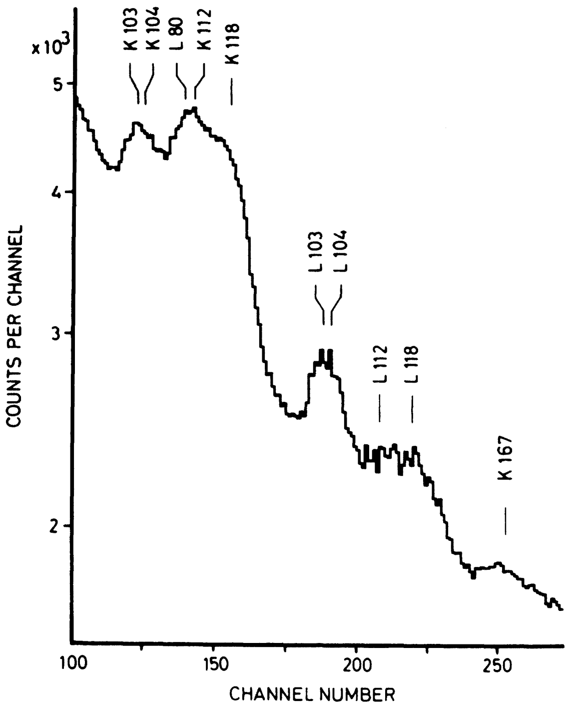

FIG. 2. Low-energy conversion electron spectrum of the decay of ^{140}Cs recorded with a Si(Li) detector.

x-ray detector and the calculation was similar to that of Ref. 8. This determination can be made due to the fact that the conversion coefficients of the more important transitions above 14 keV are known.

In this way we obtained an upper limit for the α_L conversion coefficient of the 14-keV transition: $\alpha_L < 36$. Both $E1$ and $M1$ multipolarities agree with this limit. From level scheme considerations, (see Sec. IV) an $E1$ multipolarity could be ruled out. If so, the $M1$ multipolarity for the 14-keV transition allows one to assert that a $E2$ multipolarity for the 38- and 50-keV transitions is essentially ruled out, taking into account the detected number of L x rays.

IV. LEVEL SCHEME CONSTRUCTION AND LOG*ft* VALUES

The complete level scheme proposed is shown in Figs. 3(a)–3(c). It was constructed with the following procedure: Using our coincidence results, those of Ref. 1 tabulated as "definite" in both works, and intensity balance considerations, we constructed a preliminary level scheme with level energies adjusted by minimizing χ^2.[12] In a second step we introduced the doubtful coincidences but

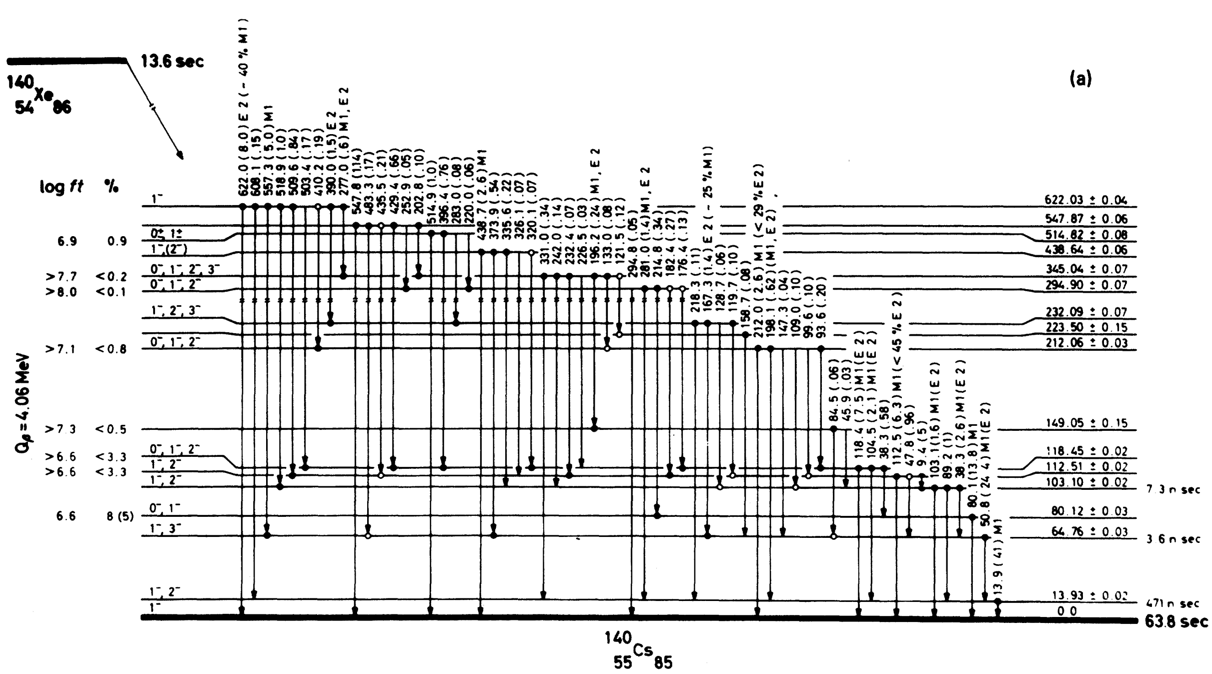

FIG. 3. (a) Low-energy region of the proposed level scheme for ^{140}Cs. Transition intensities per 100 disintegrations and adopted multipolarities are given. Dots and open circles denote "definite" and "doubtful" coincidence results, respectively. (b) Medium-energy region of the proposed level scheme for ^{140}Cs. (c) High-energy region of the proposed level scheme for ^{140}Cs.

without allowing any change in the level energies. In a third step we introduced, by sum relations, the transitions not yet included and allowed the code[12] to generate new levels under the constraint that all new levels should be connected to other levels through at least three gamma rays. The levels found were 1159.7, 1169.7, and 1193.6 keV. Up to this point the proposed level scheme is consistent enough as to allow us to perform a semiquantitative coincidence intensity estimation with the COBAL code.[12] This code provides the coincidence intensities for all the transitions linked with the gating transition, taking into account level scheme constraints and the intensities of the transitions involved. Although the numbers obtained in this way should not be considered as an absolute quantitative analysis, at least they allow a comparison with other transitions of similar intensity (see Fig.4).

A typical result is shown in Fig. 4 for the 50-keV gate. Through this analysis we observed that the 50-390 and 50-557 keV coincidences suggested as "probable" in Ref. 4 should be between 10 and 35 times stronger than the 50-462 keV coincidence established as definite by Schick *et al.*[1] Our results, instead, are consistent, as can be seen in Fig. 4. With a similar analysis we also concluded that at least 75% of the 774-keV transition deexcites the 774-keV level and no more than 25% can be placed between the 1427.59- and 653.24-keV levels. Consequently, we prefer to use a dashed line for the latter placement.

Making a detailed quantitative analysis for the 38-1177, 89-1177, 103-510, 103-1315, 510-38, and 1315-103 keV coincidences, we conclude that the postulated 9.4-keV transition (see Sec. III) has a

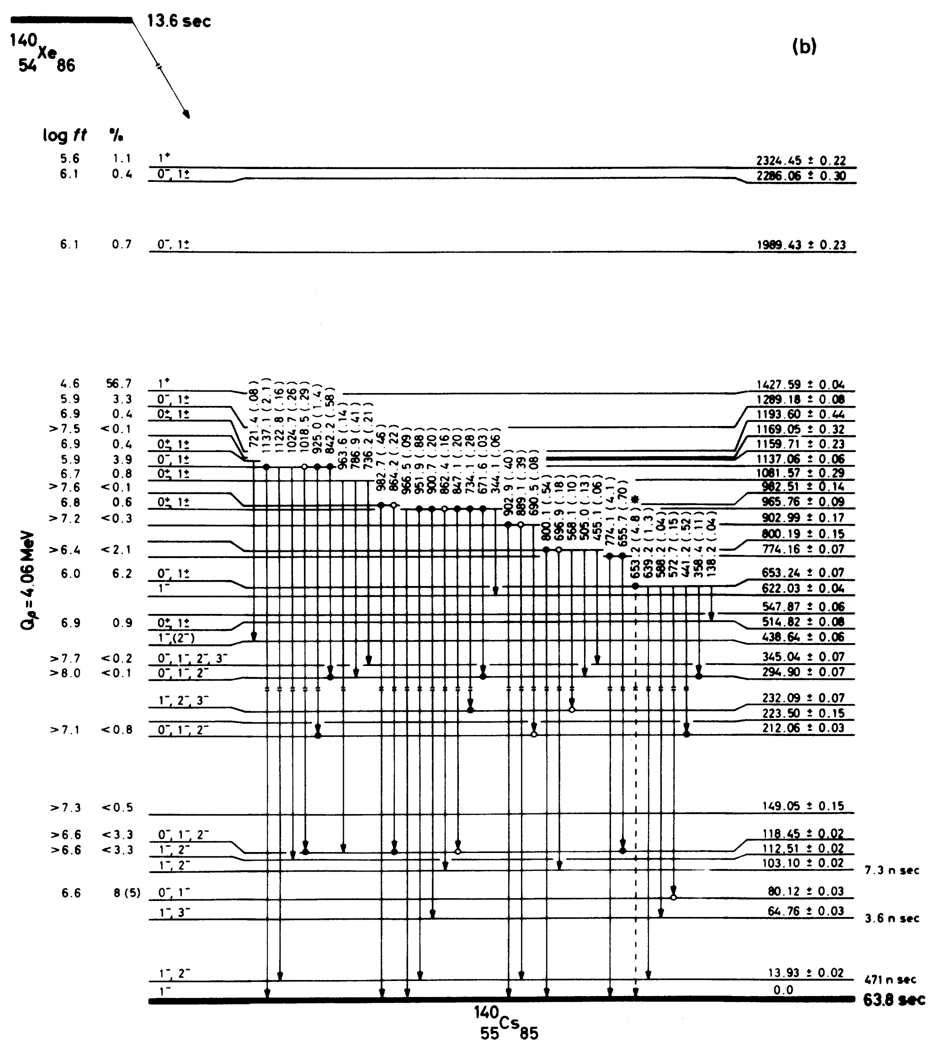

FIG. 3. *(Continued).*

total intensity of 25 ± 12 (normalized to the 805.5-keV gamma-ray intensity). Besides, we infer from this kind of analysis that the 38-keV transition is a doublet composed of a gamma ray of 38.34 keV, with a gamma intensity of 0.9%, placed between the 103.10- and 64.76-keV levels, and another one of 38.33 keV (total intensity: 2.9%), placed between the 118.45- and 80.12-keV levels.

From the proposed multipolarities for the 112- and 118-keV gamma rays and the level scheme, we deduced that an $E1$ multipolarity is ruled out for the 14-keV gamma ray. The proposed multipolarity for the other low-energy transitions (Table I) and the calculated intensities per hundred decays allows us to calculate the beta feedings and logft values for the excited levels. We used a Q_β = 4.06 MeV (Ref. 13) and a half-life of 13.6 s.[14,15] The results are shown in Fig. 3. Except for the 103.10- and 653.24-keV levels our logft values are in satisfactory agreement with those of Ref. 2. Briefly, the differences are (i) 103.10-keV level: the postulated 9.4-keV transitions placed between the 112.51- and 103.10-keV levels replaces the previously assigned beta feeding, making it zero now; (ii) 653.24-keV level: the proposed logft is tentative as the 653-keV transition is placed twice in the level scheme.

V. SPIN-PARITY ASSIGNMENTS AND DISCUSSION

J^π assignments were made for 25 levels, three of them unequivocally, based on our assigned multipolarities and logft values. The 0^+ possibility for the 622.03-, 438.64-, 64.76-, and 13.93-keV and ground-state levels was ruled out by angular correlation measurements.[3] In this way we also ruled out the 2^- possibility for the 64.76 keV level. We propose a $1^-, 3^-$ assignment for that level, because the absence of beta feeding is a weak argument to propose only a 3^- as in Ref. 2.

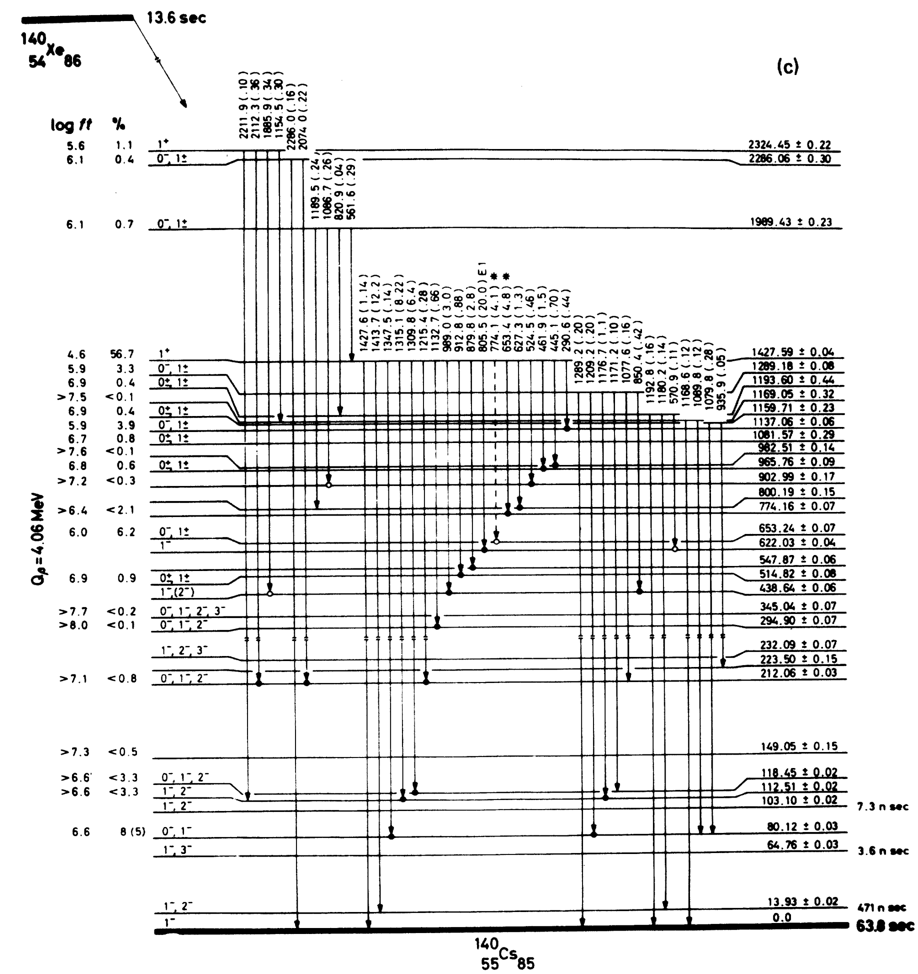

FIG. 3. *(Continued)*.

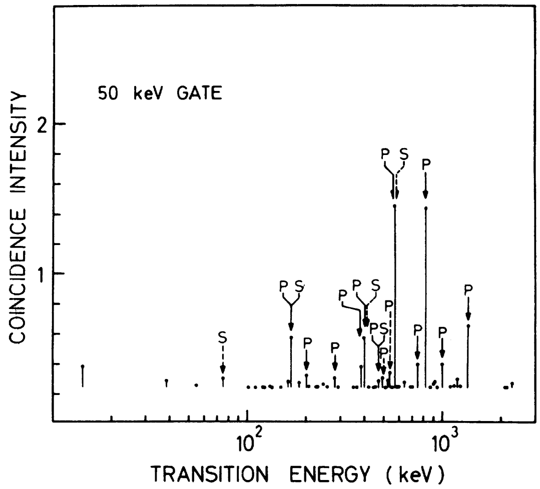

FIG. 4. Semiquantitative coincidence intensity estimation for the 50 keV gate. Coincidences observed by Shick *et al.* (Ref. 4) are marked with *S*. Coincidences observed in the present work are marked with *P*. Solid and dashed lines show definite and doubtful coincidences results, respectively.

For the sake of completeness we also include the measured half-lives of excited levels.[15,16] We adopted the values of Ref. 16. The hindrance factors compared to the independent-particle Weisskopf estimates range from 10^2 to 10^3.

In the recent compilation for the 140 mass chain by Peker,[6] definite spin and parity was assigned to several levels. Our results show agreement with the choices for the 1427.6 and 2324.4 keV levels, but for the other cases we prefer to leave all the J^π possibilities, although without parentheses, taking into account our results. We adopted a zero ground-state beta feeding instead of that of Ref. 11, as was discussed above. The improvements provided by our work on the data used for the compilation of Peker[6] are (a) the existence of a 9.4-keV gamma ray which connects the levels of 112.5 and 103.1 keV; (b) the placement of two transitions of about 38 keV: one of 38.33 keV with relative total intensity of 2.9 ± 1.5 between the 118.5- and 80.1-keV levels and another of 38.34 keV, placed between the 103.1- and 64.8-keV levels, with relative intensity of 12.7 ± 3.4 (both placements were made through the analysis of coincidence results); and (c) the elimination of the inconsistencies in the previously reported coincidence results.

The shell model orbitals available for low-lying levels of ^{140}Cs are $\pi g_{7/2}$, $\pi d_{5/2}$, $\nu f_{7/2}$, and $\nu h_{9/2}$. The firmly established negative parity for those levels gives $\pi g_{7/2} \times \nu f_{7/2}$, $\pi g_{7/2} \times \nu h_{9/2}$, $\pi d_{5/2} \times \nu h_{9/2}$, and $\pi d_{5/2} \times \nu f_{7/2}$ as possible configurations. From the systematic behavior of odd-A Cs isotopes $\pi g_{7/2} \times \nu f_{7/2}$ is the more plausible configuration for those states, even though coupling to a 3^- state as in the ^{138}Cs ground state seems to be lost.[10] Instead, the ground-state spin measurement[4] suggests an $I = 1$ value. Besides, our internal conversion coefficients and those of Ref. 2 ensure negative parity for the ground-state level.

In the high-energy region $J^\pi = 1^+$ is proposed for the 1427.59- and 2324.45-keV levels. The particle configurations involved in both levels were not available, as one could expect, in the low-lying levels. The measurement of the internal conversion coefficient of the deexciting gamma transitions could improve the present information but the high energy and low intensity of those transitions make such measurements very difficult.

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