Decay of ^{120}Ba

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The decay of ^{120}Ba has been studied with an on-line isotope separator. Its half-life was determined to be $t_{1/2}=24\pm2$ s. A decay scheme is proposed, based on γ-γ, γ-X, and γ-β^+ coincidence measurements, which takes account of all 16 observed γ rays. The total decay energy was measured to be $Q_{EC}=50\pm0.3$ MeV.

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I. INTRODUCTION

Nuclei in the transitional region around ^{120}Ba are not especially well studied even though they are of considerable interest, particularly as candidates for the appearance of shape coexistence. In the case of the light barium isotopes, there are technical problems that have made their study difficult: on the one hand, the half-lives are too short for chemical separation; on the other hand, in experiments with isotope separators, the barium isotopes are generally swamped by the efficiently ionized cesium isobars.

The first observation of the decay of ^{120}Ba was claimed in 1977 by Bogdanov *et al.*, [1] who studied isotope-separated products from the ^{32}S+^{96}Ru reaction at 180–190 MeV. They reported two γ rays, at 51 and 182 keV, with a half-life of 32±5 s, which they attributed to ^{120}Ba. The identification was not definitive, however: although the mass of the nuclide responsible was established by the separator, no x-ray coincidences were observed to identify the element unambiguously. Until the present work, no other studies of ^{120}Ba decay have been reported.

Gamma-ray transitions in the daughter, ^{120}Cs, have been reported from in-beam measurements with the reactions ^{160}Cd(^{16}O,pn)^{120}Cs at 52.5–66 MeV [2] and ^{112}Sn(^{12}C,$p3n$)^{120}Cs at 86 MeV [3]. In addition, Genevey-Rivier *et al.* [4] have found evidence that ^{120}Cs has two β-decaying isomers with approximately the same half-life. One of them, presumably the ground state, has been determined [5] to have $J=2$. The other has relatively high spin [4,6] since its β-decay populates states in ^{120}Xe up to 8^+. Only one band of states in ^{120}Cs has been determined [3] from the ^{112}Sn+^{12}C experiment. The γ rays observed in the reaction ^{106}Cd+^{16}O were quite different in energy and were not assigned by the authors [2] to a level scheme.

We report here the first definitive study of the decay of ^{120}Ba. Sixteen β-delayed γ rays have been positively identified and the half-life and Q_{EC} for ^{120}Ba have been measured. A decay scheme is proposed.

II. EXPERIMENTAL PROCEDURE

The ^{120}Ba activity was produced in the reaction ^{106}Cd(^{16}O,$2n$)^{120}Ba. The mass-120 reaction products were isotope-separated on line, deposited on the tape of a tape-transport system, and moved periodically to a counting location where β-γ, γ-γ, and X-y coincidences were recorded.

A 78-MeV-^{16}O^{6+} beam was used from the upgraded MP Tandem at the Chalk River TASCC (Tandem Accelerator Superconducting Cyclotron) facility. The beam entered a 35-cm^3 helium-filled target chamber through a molybdenum window, 3.2 mg/cm^2 thick, and bombarded a 2.0-mg/cm^2 self-supporting ^{106}Cd foil (80% enriched) after losing ~10 MeV in the window. In order to avoid damaging the target (or window) at beam currents up to 1 μA (electrical), we defocused the beam spot at the target to about 5 mm diameter.

Reaction products recoiling out of the target foil thermalized in the helium gas (at ~100 kPa) and attached themselves to NaCl aerosol clusters that were continuously added to the helium stream. The clusters and reaction products were then swept through a short stainless-steel capillary, 2.5 m long, to the skimming orifice at the entrance of the He-jet ion source [7] of the Chalk River on-line isotope separator [8]. The working temperature of the ion source was about 1700 K. At this temperature, it was found that the yield of barium was significantly favored over that of cesium if 0.5% CF_4 was added to the usual argon support gas and the isotope separator was set to analyze the fluorides of the two elements. It was under these conditions of "flourination" that our experimental data were taken, with the isotope separator set for mass 139 (^{120}BaF). On average, our production of ^{120}Ba was at the rate of 3000 atom/s.

Separated products were implanted in the aluminized-Mylar tape of a tape-transport system at the end of the isotope-separator's beam-transport line. After a 60-s collection period, the activity on the tape was transported through two differentially pumped exit chambers to a fielded location in air 50 cm away; counting began ~200 ms after the move was initiated, and continued for 60 s.

While the first sample was being counted, the next one was being collected.

Two different experimental arrangements were used, one for β-γ coincidence measurements, the other for $\gamma(X)$-$\gamma(X)$ coincidences. In each arrangement, two detectors were placed face to face on either side of the tape. For both, the distance from the tape to the detector window was 1 cm.

In the first experiment, which comprised about 4.5 h of counting time, the β detector and one γ-ray detector was mounted. The former was hemispherical in shape, 10 cm in diameter, and made from Chinese ST401 plastic scintillator. The latter was a HPGe detector with 40% relative efficiency. In the second experiment, which ran for about 7 h of total counting time, the β detector was replaced by a second γ-ray detector, a Ge(Li) detector with 16% relative efficiency. In both experiments, we recorded γ-ray singles events and three-parameter coincidences, either β-γ-t or γ-γ-t, where t was the time of each event after the beginning of a counting period. Since the thickness of the beryllium windows of both γ-ray detectors was 0.5 mm, we could observe the x rays of cesium and xenon.

III. EXPERIMENTAL RESULTS

A. Isotope separation of barium

The ^{16}O bombardment of ^{106}Cd can produce only three isotopes with $A = 120$, viz., ^{120}Ba, ^{120}Cs, and ^{120}Xe. Since xenon, as a noble gas, has very poor transport efficiency through a helium-jet-skimmer system, only the first two were observable at the output of the isotope separator. Unfortunately, barium is not ionized nearly as efficiently as the alkali metal, cesium, with the result that γ rays following the β decay of ^{120}Cs ($t_{1/2} \sim 60$ s) dominated the β-coincident γ-ray spectrum recorded for $A = 120$ [see Fig. 1(a)]. Following earlier workers [9,10] we introduced CF_4 to the ion-source support gas and, at 0.5% admixture, recorded the γ-ray spectrum of Fig. 1(b) with the separator set for $A = 139$. Evidently, the observed production of cesium is reduced by more than a factor of 20 relative to barium; the production rate of barium in the form ^{120}BaF is roughly comparable to that of ^{120}Ba without fluorination. All of these results presented here were obtained with flourination.

B. Gamma-ray measurements

The γ-ray singles spectrum was measured up to 2 MeV. The results below 350 keV are presented in Fig. 2, and samples of the γ-$\gamma(X)$ coincidence data appear in Fig. 3 and 4. Sixteen γ-ray peaks were attributed (see following arguments) to the decay of ^{120}Ba; they are marked in Fig. 1 and their energies and relative intensities are listed in Table I. All γ-ray peaks observed above 350 keV could be attributed to room background or the decay of ^{120}Cs. Coincidence data are summarized in Table II. Half-life data were also obtained for most γ-ray peaks in both experimental arrangements (see, for example, Fig. 5); the half-life thus established for ^{120}Ba is 24±2 s.

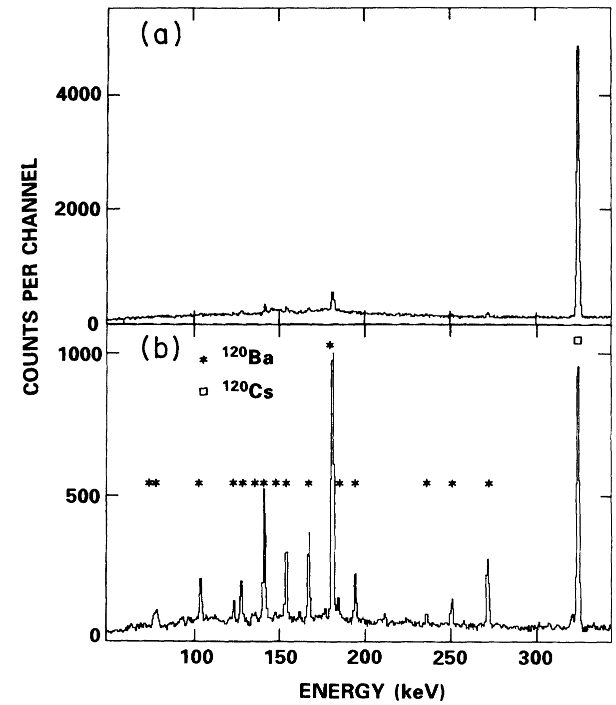

FIG. 1. Gamma-ray spectra observed in coincidence with betas: (a) for $A = 120$ without CF_4 introduced into the ion source and (b) for $A = 139$ with CF_4 present in the ion-source support gas. The peaks are identified by their β-decaying precursors.

Since only ^{120}Cs and ^{120}Ba could be produced and isotope separated in this experiment, all γ rays in Fig. 2 must be attributable to one or another of these isotopes and their daughters, or to the measured room background. The decay of ^{120}Cs is well known [4,6], so the γ rays from ^{120}Ba could, in large measure, be identified by a process of elimination. In fact, the identification is more positive, with all but one of the γ rays listed in Table I having been observed in coincidence with the K_α x rays of cesium (see Table II and Fig. 3). The exception, at

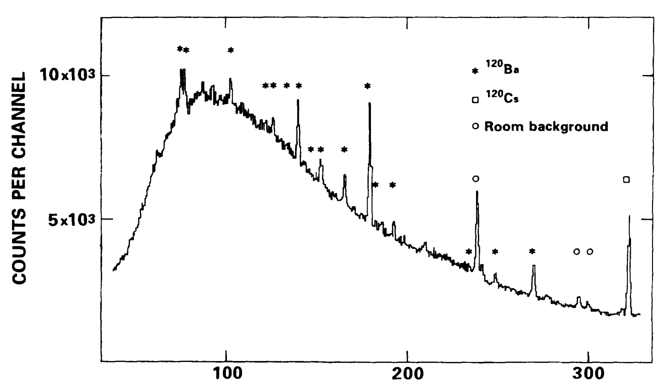

FIG. 2. Part of the measured γ-ray singles spectrum observed following the decay of mass-separated activities with $A = 139$ under fluorination conditions. The 16 γ-ray peaks associated with ^{120}Ba decay were identified through β-γ and γ-$\gamma(x)$ coincidences and are marked in the spectrum.

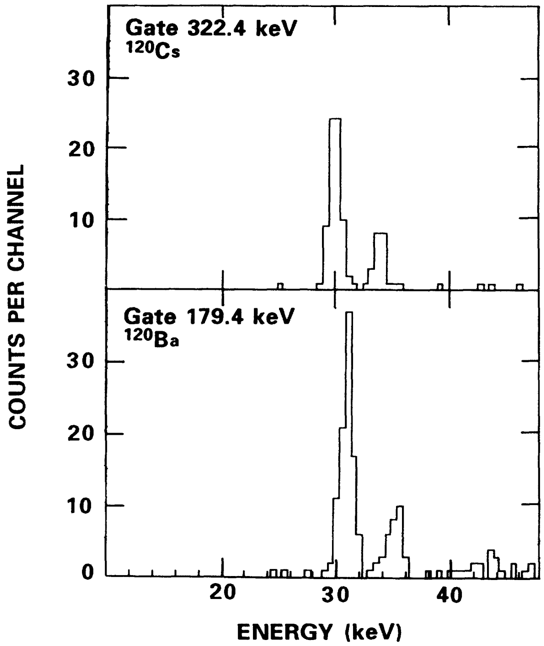

FIG. 3. X-ray spectra gated by indicated γ rays following the decay of ^{120}Ba and ^{120}Cs.

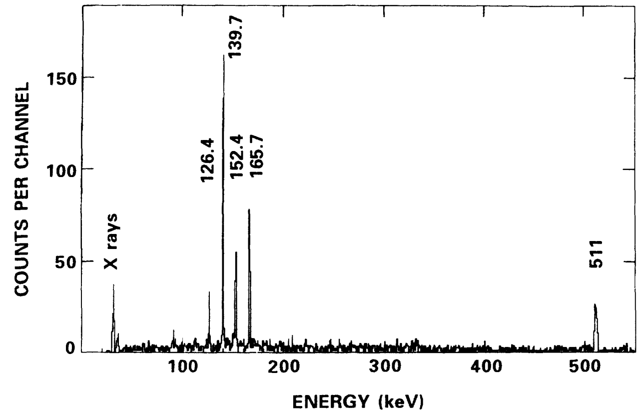

FIG. 4. Gamma-ray spectrum gated by the 179.4-keV gamma ray following the decay of ^{120}Ba; energies are labeled in keV.

146.0 keV, is too weak for us to be certain of an x-ray coincidence but its energy corresponds to an energy-level difference in the proposed decay scheme (see Fig. 6). Note that the $K\alpha$ x-ray peaks from cesium and xenon could not be resolved from one another in our detector but, as illustrated in Fig. 3, they are clearly identifiable by their energy in the coincidence spectra gated on individual γ rays.

C. Decay scheme

The coincidence data and energy sums lead us to suggest the decay scheme shown in Fig. 6. It accounts for all 16 γ-ray peaks listed in Table I, although three are only tentatively placed. The 134.8-keV peak is not seen in coincidence with any other γ ray, so it is placed as a transition directly to the ground state; however, its relative weakness means that the absence of observed coincidences is far from definitive. Coincidence data for the 122.1-keV transition is possibly contradictory (a definite coincidence with 102.6- and 182.6-keV γ rays, but a possible coincidence with the 234.3-keV γ ray: see Table II) so its placement, too, is tentative. Finally, the 146.0-keV γ ray is too weak to produce any useful coincidence data, so it is placed solely on the basis that its energy agrees with the energy difference between two levels independently determined.

It should be particularly noted that the observed data could only be reconciled with a consistent decay scheme if a 13.4-keV transition is postulated between the excited states at 192.8 and 179.4 keV. Such a transition could not have been directly observed in our experiment since it is below the energy threshold in our γ-ray detectors and, in any case, would be highly converted; thus, we have no direct information on the branching in the decay of the 192.8-keV state. However, by gating on the 126.4- and 152.4-keV γ rays (which feed the 192.8-keV state) we obtained from the coincidence data a ratio of 0.57 ± 0.06 for the intensity of the 192.8-keV γ ray relative to the 179.4-keV one. If it is assumed that the 179.4- and 192.8-keV transitions have the same multipolarity, then the intensity of the 13.4-keV *transition* is 30 ± 6 % of the intensity of the 179.4-keV γ *ray*. If the 192.8-keV transition is fur-

TABLE I. Gamma rays from ^{120}Ba β decay.

Energy (keV)	Relative γ-ray intensity	Position in decay scheme[a]	Energy (keV)	Relative γ-ray intensity	Position in decay scheme
75.2 ± 0.3	10 ± 4	$10\rightarrow6$	152.4 ± 0.2	14 ± 3	$10\rightarrow4$
76.9 ± 0.3	9 ± 4	$3\rightarrow1$	165.7 ± 0.2	23 ± 4	$10\rightarrow3$
102.6 ± 0.2	9 ± 3	$1\rightarrow0$	179.4 ± 0.2	100	$3\rightarrow0$
122.1 ± 0.2	6 ± 3	$11\rightarrow7$	182.6 ± 0.2	7 ± 2	$7\rightarrow1$
126.4 ± 0.2	7 ± 2	$8\rightarrow4$	192.8 ± 0.2	17 ± 3	$4\rightarrow0$
134.8 ± 0.3	<5	$(2\rightarrow0)$	234.3 ± 0.2	<10	$9\rightarrow1$
139.7 ± 0.2	38 ± 6	$8\rightarrow3$	248.9 ± 0.2	14 ± 4	$5\rightarrow0$
146.0 ± 0.3	<4	$(5\rightarrow1)$	269.9 ± 0.2	43 ± 7	$6\rightarrow0$

[a] Level number identification is given in Table III.

TABLE II. Gamma-gamma coincidences observed in the decay of ^{120}Ba.

Gate \ Lines in coinc.[a]	K_α(Cs)	75.2	76.9	102.6	122.1	126.4	134.8	139.7	146.0	152.4	165.7	179.4	182.6	192.8	234.3	248.9	269.9
75.2[b] 76.9[b]	×			×				(×)									×
102.6	×		×		(×)				(×)		(×)		×		×		
122.1	×			×									×				
126.4	×											×		×			
134.8	×																
139.7	×		(×)									×					
146.0																	
152.4	×											×		×			
165.7	×			(×)								×					
179.4	×					×		×		×	×						
182.6	×			×	×												
192.8	×					×				×							
234.3	×			×	(×)												
248.9	×																
269.9	×	×															

[a] Statistically significant coincidences are marked by ×; possible coincidences are marked by (×).
[b] The 75.2- and 76.9-keV peaks were both included in a single gate.

ther assumed to be $M1$, then the 192.8-keV state can be deduced to decay 60±12 % by the 13.4-keV transition.

The level energies with expermental uncertainties are also listed in Table III together with the β^+ and electron-capture side feeding. The side feeding is calculated as the difference between the γ-ray feeding and decay of each level; we took internal conversion into account assuming all transitions to be pure $M1$. This assumption is based on the fact that all allowed β transitions from the 0^+ ground state of the even-even ^{120}Ba must feed 1^+ states in ^{120}Cs, and the $J=2$ ground state of the even-even ^{120}Ba must feed 1^+ states in ^{120}Cs, and the

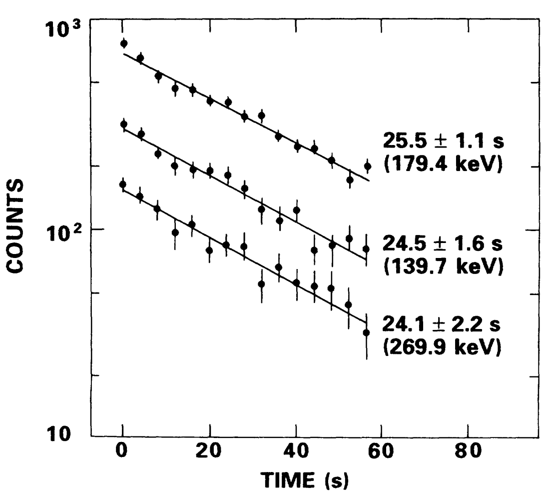

FIG. 5. Sample decay curves measured for β-coincident γ rays following the decay of ^{120}Ba.

$J=2$ ground state of that nucleus is most likely also to have positive parity. It should also be noted that the side-feeding values and their quoted uncertainities take account only of the observed γ rays (and the 13.4-keV transition) and their relative intensities as listed in Table I; no provision is made for other unobserved transitions [11].

D. The total decay energy Q_{EC}

Positron spectra were obtained in coincidence with all strong γ-ray lines from ^{120}Ba. Following Wouters [12] we have adopted a Gaussian response function to fit the β spectra, viz.,

$$R(E,E')=[S(E')\sqrt{2\pi}]^{-1}\exp[-(E-E')^2/2S(E')^2]$$

such that

$$\int R(E,E')dE=1 .$$

Here, $S(E')$ represents the energy resolution of the β detector, which is assumed to be proportional to the square root of the energy of the detected electron; i.e.,

$$S(E')=S_0(E'/E_0)^{1/2} .$$

In our case, $S_0=250$ keV and $E_0=1.0$ MeV as determined from the measured energy resolution of the conversion electron from the decay of ^{207}Bi.

To analyze the measured β spectra, a computer program was used to incorporate the effects of the response function onto the theoretical spectrum shape. After several iterations of the program, each measured β spectrum was converted into a "real" β spectrum, from which a Fermi-Curie plot was made and the end-point energy determined. Several examples are shown in Fig. 7. Energy calibration of the β spectrum was established by mea-

TABLE III. Levels in ^{120}Cs populated in the decay of ^{120}Ba.

Level number	Level energy (keV)	Side feeding $I_{\beta^+}+I_{EC}(\%)$	logft[a]	Spin and parity
0	0	0[b]	≥ 8.5[b]	2[b]
1	102.6±0.2	<1	<6.1	
2[c]	134.8±0.3	<3	>5.6	
3	179.4±0.2	15±7	5.0±0.2	1^+
4	192.8±0.2	9±4	5.3±0.2	1^+
5	248.9±0.2	6±2	5.4±0.2	1^+
6	269.9±0.2	<13	>4.3	
7	285.2±0.3	<1	>6.0	
8	319.2±0.2	26±3	4.7±0.1	1^+
9	336.9±0.3	<5	>5.3	
10	345.1±0.2	33±6	4.6±0.2	1^+
11[c]	407.3±0.4	4±2	5.5±0.3	1^+

[a] Calculation based on $t_{1/2}=24\pm2$ s and $Q_{EC}=5.0\pm0.3$ MeV.
[b] Because the ground-state spin is known [5] to be 2, the logft and side feeding are taken to be characteristic of a forbidden transition.
[c] Level unconfirmed.

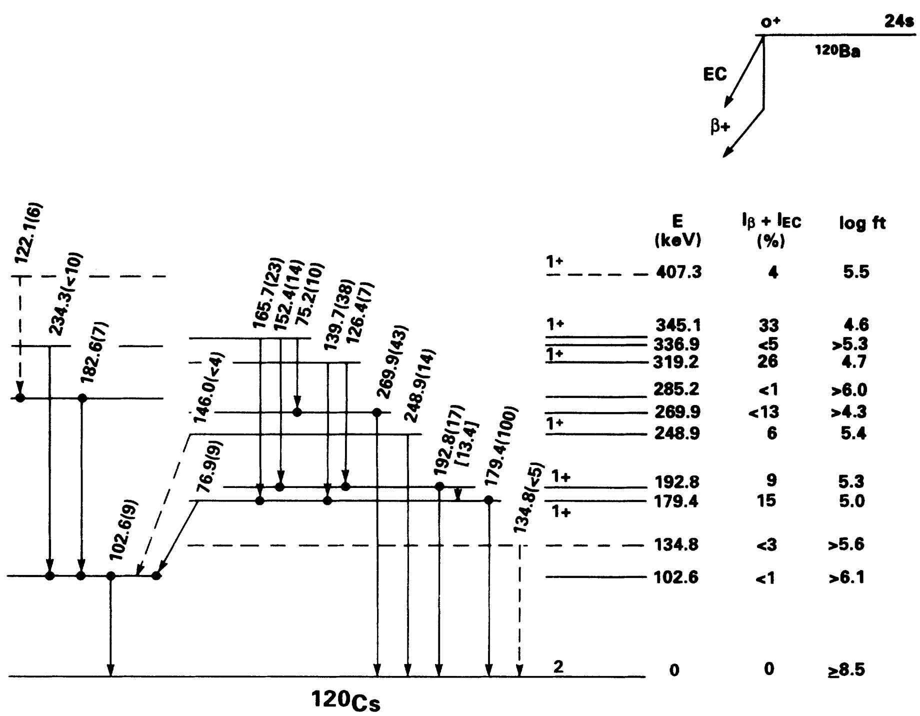

FIG. 6. Proposed decay scheme of ^{120}Ba. Dashed levels and transitions should be considered as tentative.

TABLE IV. The total decay energy, Q_{EC}, of ^{120}Ba.

Level Populated in ^{120}Cs (keV)	Coincident γ rays (keV)	Measured β end-point energy (MeV)	Derived Q_{EC} (MeV)	Q_{EC} Uncertainty Stat (MeV)	Syst (MeV)
269.9	269.9	3.69	5.00[a]	0.08	
319.2	126.4,139.7	3.59	4.93	0.08	
345.1	152.4,165.7	3.64	5.01	0.08	
	Average		4.98	0.05	0.25

[a] The level at 269.9 keV is also fed by a 75.2-keV γ ray from the level at 345.1 keV (see Fig. 6); the derived Q_{EC} takes account of this double feeding.

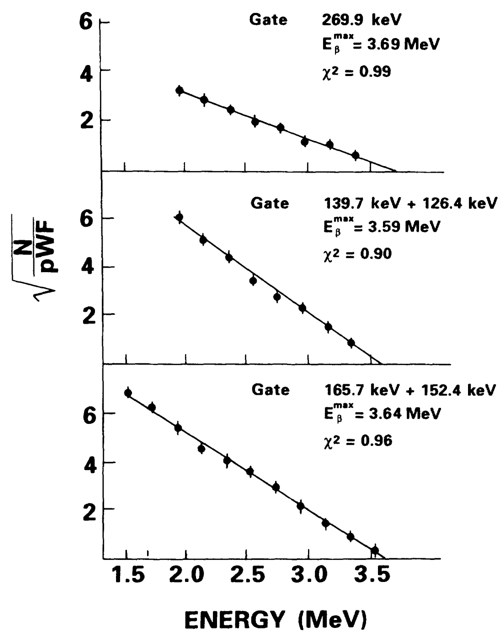

FIG. 7. Fermi-Curie plots for a representative sample of β spectra measured in coincidence with identified γ rays.

surements with standard sources of ^{90}Y and ^{152}Eu, and with in-beam measurements on ^{120}Cs ($Q_{EC}=7.990$ MeV; see Ref. [13]). The results for ^{120}Ba decay, based on the decay scheme of Fig. 6, are listed in Table IV; they show good internal consistency and yield a final result of $Q_{EC}=5.0\pm0.3$ MeV for the decay of ^{120}Ba. This result is consistent with the value 4.80±0.41 MeV predicted by Wapstra *et al.* [13] on the basis of mass systematics.

IV. DISCUSSION

The ground state of ^{120}Ba can safely be assumed to be 0^+. Because the ground-state spin of ^{120}Cs is known [5] to be $J=2$, the β transition populating it from ^{120}Ba must be first-forbidden unique or second forbidden, with a log*ft* greater than 8.5 (see Ref. [14]). The ground-state transition thus being negligible, the β-decay side feeding to other ^{120}Cs levels can be determined from the observed γ-ray intensities; it is this procedure that was used to establish the percentages shown in Table III and Fig. 6. The log*ft* values also shown there were calculated with the tables of Gove and Martin [15] and were based on our experimental results for side feeding, half-life, and Q_{EC} value.

Any levels in ^{120}Cs fed by allowed β decay must have $J^\pi=1^+$. The criterion for allowed β^+ decay from a 0^+ state is — according to Raman and Gove [14]—log*ft* <5.9. Consequently, we assign $J_\pi=1^+$ to levels 5, 8, 10, and 11, and to at least one of levels 3 and 4; the side feeding to the last two levels cannot be distinguished because of the unobserved 13.4-keV transition between them.

Our experimental results for ^{120}Ba differ significantly from the only previous decay study. Although the half-life measured by Bogdanov *et al.*, [1] 32±5 s, is not inconsistent with our result of 24±2 s, their two observed γ rays at 51 and 182 keV (with no quoted error bars) do not agree with our data: we observe no γ ray at 51 keV and only a weak peak at 182.6±0.2 keV. It should be noted, though, that our strongest γ-ray peak occurs at 179.4±0.2 keV.

Comparison of our results with the in-beam studies [2,3] of ^{120}Cs produced directly in heavy-ion reactions shows few similarities, but this is not surprising since β decay populates only low-spin states. Conrad and Repnow [2] do observe γ rays at 102.5 keV (cf. 102.6 keV; see Table I) and 180 keV (cf. 179.4 keV), but they observe three more with no similarity to our observations, and Quader *et al.* [3] observe six γ rays with only one (at 127 keV) showing any similarity in energy with those listed in Table I.

With positive identification of A and Z, the present work puts the decay of ^{120}Ba on a sound footing. Further work is required, however, before the states in ^{120}Cs are understood sufficiently to permit any comparison with model calculations.

[1] D. D. Bogdanov, A. V. Demyanov, V. A. Karnaukhov, L. A. Petrov, A. Plohocki, V. G. Subbotin, and J. Voboril, Nucl. Phys. **A275**, 229 (1977).

[2] J. Conrad and R. Repnow, Z. Phys. A **276**, 403 (1976).

[3] M. A. Quader, C. W. Beausang, P. Chowdhury, V. Garg, and D. B. Fossen, Phys. Rev. C **33**, 1109 (1986).

[4] J. Genevey-Rivier, A. Charvet, G. Marguier, C. Richard-Serre, J. D'Auria, A. Huck, G. Klotz, A. Knipper, and G. Walter, Nucl. Phys. **A283**, 45 (1977).

[5] C. Thibault, F. Touchard, S. Büttgenbach, R. Klapisch, M. de Saint Simon, H. T. Duong, P. Jacquinot, P. Juncar, S. Liberman, P. Pillet, J. Pinard, J. L. Vialle, A. Pesnelle, and G. Huber, Nucl. Phys. **A367**, 1 (1981).

[6] A. Hashizume, Y. Tendow, and M. Ohshima, Nucl. Data Sheets **52**, 641 (1987).

[7] H. Schmeing, J. S. Wills, E. Hagberg, J. C. Hardy, V. T. Koslowsky, and W. L. Perry, Nucl. Instrum. Methods **B26**, 321 (1987).

[8] H. Schmeing, J. C. Hardy, E. Hagberg, W. L. Perry, J. S. Wills, J. Camplan, and B. Rosenbaum, Nucl. Instrum. Methods **139**, 335 (1976).

[9] H. L. Ravn, S. Sundell, and L. Westgaard, J. Inorg. Nucl. Chem. **37**, 153 (1975).

[10] J. C. Putaux, J. Obert, L. Kotfila, B. Roussiere, J. Sauvage-Letissier, C. F. Liang, A. Peghaire, P. Paris, and J. Giroux, Nucl. Instrum. Methods **186**, 321 (1981).

[11] J. C. Hardy, L. C. Carraz, B. Jonson, and P. G. Hansen, Phys. Lett. **71B**, 307 (1977).

[12] J. M. Wouters, H. M. Thierens, J. Äystö, M. D. Cable, P. E. Haustein, R. F. Parry, and Joseph Cerny, Phys. Rev. C **27**, 1745 (1983).

[13] A. H. Wapstra, G. Audi, and R. Hoekstra, At. Data Nucl. Data Tables **39**, 281 (1988).

[14] S. Raman and N. B. Gove, Phys. Rev. C **7**, 1995 (1973).

[15] N. B. Gove and M. J. Martin, Nucl. Data Tables **10**, 206 (1971).