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E. Achterberg
F. C. Iglesias
A. E. Jech
J. A. Moragues
M. L. Pérez
J. J. Rossi
W. Scheuer
J. F. Suárez

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NIVELES DE ^{86}Kr ALIMENTADOS EN EL DECAIMIENTO DE ^{86}Br

E. Achterberg*, F.C. Iglesias*, A.E. Jech*, J.A. Moragues*,
M.L. Pérez*, J.J.Rossi*, W. Scheuer* y J.F. Suarez*.

RESUMEN

El decaimiento del ^{86}Br fue estudiado mediante detectores de Ge (Li) y aplicando técnicas de separación de masas "en línea" con la producción de productos de fisión de ^{235}U. Por medio de la comparación de vidas medias, se pudieron asignar 19 transiciones como pertenecientes a este decaimiento. Se midió la vida media de 10 de ellas, obteniéndose un promedio de 59 ± 4 seg. Se proponen los siguientes niveles del ^{86}Kr cuyas energías están expresadas en KeV y el valor $J\pi$ indicado entre paréntesis: 1564,62±0,09 (2^+), 2349,60±0,14 (1,2), 2850,2±0,4, 2926,24±0,13 (1,2), 3099,20±0,16 (3^-), 4315,75±0,17 $(2^-,3^-)$, 5406,6±0,5 (1,2), 5519,0±0,9 $(1^-,2^-)$, y 6209,9±0,5 $(1^-,2^-)$.

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* CNEA, Departamento de Física Nuclear.

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Levels of ^{86}Kr Fed in the Decay of ^{86}Br[†]

E. Achterberg, F. C. Iglesias, A. E. Jech,* J. A. Moragues,* M. L. Pérez,* J. J. Rossi,
W. Scheuer, and J. F. Suárez
Departamento de Física Nuclear, Comisión Nacional de Energía Atômica, Buenos Aires, Argentina

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The decay of ^{86}Br has been studied with high-resolution Ge(Li) detectors by applying on-line mass-separation techniques to ^{235}U fission products. 19 transitions were positively assigned to this decay through half-life comparisons, and for 10 of them direct measurements of the half-life were performed, yielding an average value of 59 ± 4 sec. Levels for ^{86}Kr are proposed at (J^{π} within parentheses): 1564.62 ± 0.09 keV (2^+), 2349.60 ± 0.14 keV (1,2), 2850.2 ± 0.4 keV, 2926.24 ± 0.13 keV (1,2), 3099.20 ± 0.16 keV (3^-), 4315.75 ± 0.17 keV (2^-, 3^-), 5406.6 ± 0.5 keV (1,2), 5519.0 ± 0.9 keV (1^-, 2^-), and 6209.9 ± 0.5 keV (1^-, 2^-).

I. INTRODUCTION

The nucleus ^{86}Kr has four protons less than a filled doubly magic core. Both the feasibility of a shell-model description and the possibility of obtaining information about the new core through the ^{86}Kr spectrum makes this nucleus a very interesting object for nuclear physicists.

Although Stehney and Steinberg[1] discovered 54-sec ^{86}Br in 1962 through the ^{86}Kr(n,p) reaction, other authors [2,3] obtained it as a ^{235}U fission product and, from its decay, studied the level structure of ^{86}Kr. However, when the ^{86}Br activity is produced in this way, complicated fast chemical techniques are generally required to separate the Kr, I, and Xe radioactive isotopes. Once this is accomplished it is still difficult to avoid contamination due to other Br isotopes, especially ^{87}Br, which has almost the same half-life as ^{86}Br. The only successful attempt to separate ^{86}Br with this approach has been made by Williams and Coryell[2] who exploited the difference in the half-lives of the Se precursors, and performed singles and coincidence γ-ray spectroscopy with NaI(Tl) detectors. Recently, Lundán[3] studied the decay of the ^{86,87}Br mixture with Ge(Li) detectors. His results are in partial disagreement with those of Williams and Coryell, only six γ rays being assigned to mass 86 based on the identification given by these authors. Lundán interpreted an initial growth of the activity of some γ rays in his measurements as due to an isomeric state of 4.5 sec in ^{86}Br.

In recent years, from nuclear-reaction studies on ^{86}Kr targets, several levels have been identified[4,5] in this isotope. However, a definite spin-parity was assigned only to the first excited state.

The present work is devoted to clarifying the general features of the decay of ^{86}Br and removing the discrepancies between Refs. 2 and 3 by using on-line electromagnetic mass separation of ^{235}U fission products and high-resolution γ-ray detectors. Definite mass assignments were obtained for 19 γ rays, and a level scheme is proposed for ^{86}Kr based on our own, and on previously reported data. It contains three new levels and more than twice the number of γ rays of the only previously reported[2] level scheme. Spin-parity assignments are proposed on the basis of logft value and relative γ-ray intensities.

II. EXPERIMENTAL PROCEDURES

A. Source Production

The ^{86}Br sources were obtained at the Buenos Aires isotope separator on-line facility (IALE project) by placing a uranyl stearate target containing 16 g of uranium enriched to 90% in ^{235}U in a flux of about 10^8 thermal neutrons/cm^{2}sec. The latter was produced by the reaction ^{7}Li$(d, n)^8$Be using a 1-MV electrostatic accelerator for the deuterons. The uranyl stearate powder was enclosed in a stainless-steel container from which the rare-gas and halogen fission products were continously swept out and fed through a short pipe (50cm) into the ion source of an electromagnetic isotope separator. A complete description of the experimental setup is being published.[6]

The mass-86 ion beam was collected on a mov-

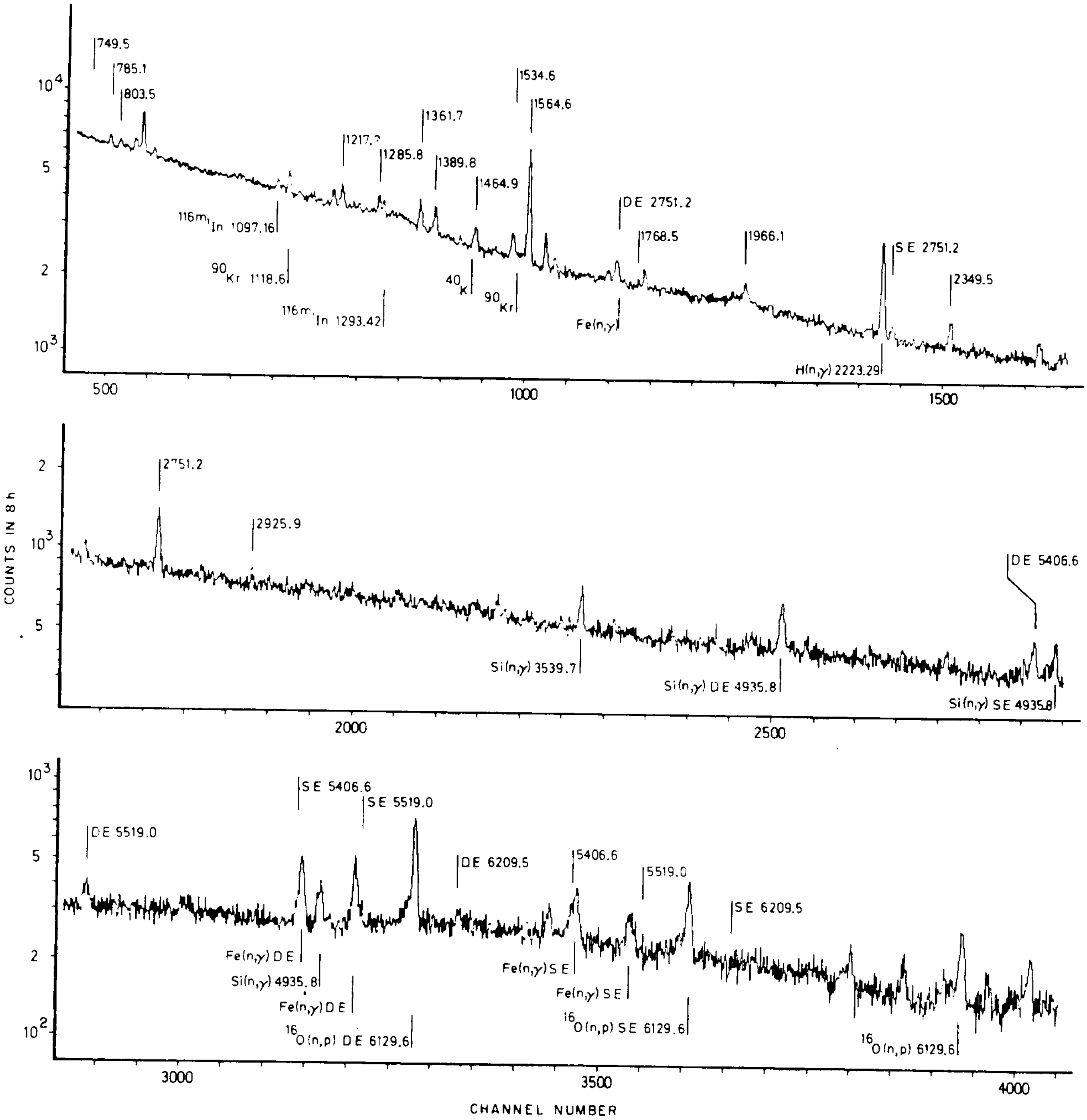

FIG. 1. Medium- and high-energy part of a typical γ-ray spectrum. The peaks labeled with their energy value in the upper part have been positively identified as belonging to the decay of ^{86}Br. Background lines, when used for energy calibration, are labeled from below. Contaminants that add to ^{86}Br-decay peaks are also indicated.

able aluminized Mylar tape which allowed the removal of undesirable long-lived activities and made it possible to vary the ratio between the ^{86}Br activity on the one hand and the background and contamination from adjacent masses on the other. In our setup the yield of Kr isotopes is much higher than that of Br isotopes and special care was necessary to avoid intense contamination during long runs. The most important contaminations were ^{85}Kr due to the presence of hydrides, and ^{87}Kr due to tails in the ion-beam profile. The absence of detectable short-lived Br activities was ascertained by looking for the corresponding Kr contamination and making use of the Kr-to-Br-activity ratio, previously determined from direct collections of the respective A-chain decay products.

B. γ-Ray Measurements

The γ-ray singles spectra were obtained using a coaxial, 45-cm^3 Ge(Li) detector coupled through conventional electronics to an analyzing system of 4096 channels. The latter is part of a 16 000-memory-word computer which also controls several fast read-out and plotting peripherals, as well as the movements of the tape collector. The resolution over short terms was 3 keV for the 1332-keV ^{60}Co line; however, since long runs – lasting up to 40 h – were necessary, the usual resolution was 4 keV for the ^{60}Co lines and 8 keV for the 6129-keV line in the decay of ^{16}N.

Peak positions and areas were obtained by manual methods and by computerized analysis procedures using the GAMANL,[7] SAMPO,[8] and ANAGAMMA[9] programs. Energy calibrations were performed using background lines due to thermal-neutron capture and to activation in the detector itself and in the shielding materials.[10-12] Well-defined transitions in ^{85}Rb[13] and ^{87}Rb,[14] and the lines arising in ^{16}N decay[12] extended the calibration range from 150 keV up to 6.2 MeV. The ^{16}N activity was produced in the cooling water of the accelerator target by the reaction ^{16}O$(n,p)^{16}$N. The corresponding adopted energies are indicated in detail in Fig. 1. The efficiency curve up to 3 MeV was obtained using the secondary standards ^{138}Xe and ^{138}Cs which, being produced on line, have a geometry identical to that of the collected ^{86}Br. These secondary standards were recently measured in our laboratory against primary standard sources.[15]

TABLE I. Energies and intensities of γ rays observed in the decay of ^{86}Br.

Present work			Lundán (Ref. 3)			Williams and Coryell (Ref. 2)	
E_γ (keV)	I_γ [a]	$T_{1/2}$ (sec)	E_γ (keV)	I_γ	Remarks	E_γ (MeV)	I_γ
499.8 ± 0.4	6 ± 5						
749.5 ± 0.7	11 ± 2						
785.14 ± 0.18	66 ± 6						
803.5 ± 0.3	44 ± 10						
1217.23 ± 0.13	120 ± 13	45 ± 15			Long-lived	1.21	100
1285.83 ± 0.14	117 ± 16	58 ± 16			Long-lived	1.28	140
1361.66 ± 0.11	180 ± 14	87 ± 23	1362 ± 2 (?)	Weak	$T_{1/2}$ uncertain	1.36	320
1389.76 ± 0.13	161 ± 14	62 ± 17					
1464.9 ± 0.3	86 ± 8	55 ± 14					
1534.6 ± 0.3	186 ± 14	49 ± 7					
1564.62 ± 0.09	1000 ± 100	60 ± 5	1565 ± 2	1000		1.56	1000
1768.5 ± 0.6 [b]	21 ± 4					1.76	65
1966.1 ± 0.3	116 ± 13	62 ± 17			Long-lived	1.97	130
2349.47 ± 0.18	152 ± 13	63 ± 12			Long-lived	2.34	170
2751.15 ± 0.26	318 ± 35	74 ± 12	2750 ± 3	380 ± 40		2.76	310
2925.9 ± 0.4	35 ± 6						
						3.6	25
						3.8	50
						4.4 (?)	
						5.3	55
5406.6 ± 0.5	62 ± 15		5403 ± 2	38 ± 3		5.44	150
5519.0 ± 0.9	44 ± 10		5518 ± 3		Mass 86 or 87		
6209.5 ± 1.0	14 ± 6		6211 ± 3	4 ± 1		6.18	25
						6.7	8

[a] The error stated for the 1564.62-keV-transition intensity has not been taken into account in calculating the error for the other intensities.

[b] Not placed in the level scheme.

The high-energy part of the efficiency curve has been determined by normalizing the above-mentioned curve to the one corresponding to the Cr(n, γ) relative intensities,[10] which was obtained from an experiment performed in the external neutron beam of the RA-3 reactor (Ezeiza, Argentina). From these measurements, and from the lines present in the background, curves corresponding to FE/SE and FE/DE area ratios have been calculated for our detector, where FE, SE, and DE stand for "full energy," "single escape," and "double escape," respectively.

C. γ-Ray Identification and Half-Life Determinations

One of the aims of the present work was to establish a positive identification for γ rays belonging to the ^{86}Br decay. This has been achieved by recording the γ spectra at different moving-tape collector speeds. Background-line intensities were not affected by the activity removal rate, but the ^{86}Br peaks and those corresponding to contamination varied according to the respective half-lives. Several γ spectra were recorded by removing the activity every 30 min and compared with those obtained when the activity was removed every 3 min. When the spectra were normalized to equal ^{86}Br activity – equal area under the previously[2, 4, 5] univocally assigned 1564.62-keV peak – the ratio for the background lines was approximately 0.6 and that for the long-lived $^{85, 87}$Kr contaminations was larger than 2. Due to poor statistics, several transitions were not clearly assigned in this way and had to be identified after analyzing a background spectrum which was measured running the neutron source alone. This was mainly necessary above 3 MeV where the contamination does not contribute and only the background lines due to reactions are in competition with the ^{86}Br γ rays.

By the procedure described above we are sure, within the experimental error, that all the γ rays labeled ^{86}Br decay with the same half-life. The following experiment was performed in order to obtain a value for the half-life of ^{86}Br from an isotopically pure sample. The isotope-separator

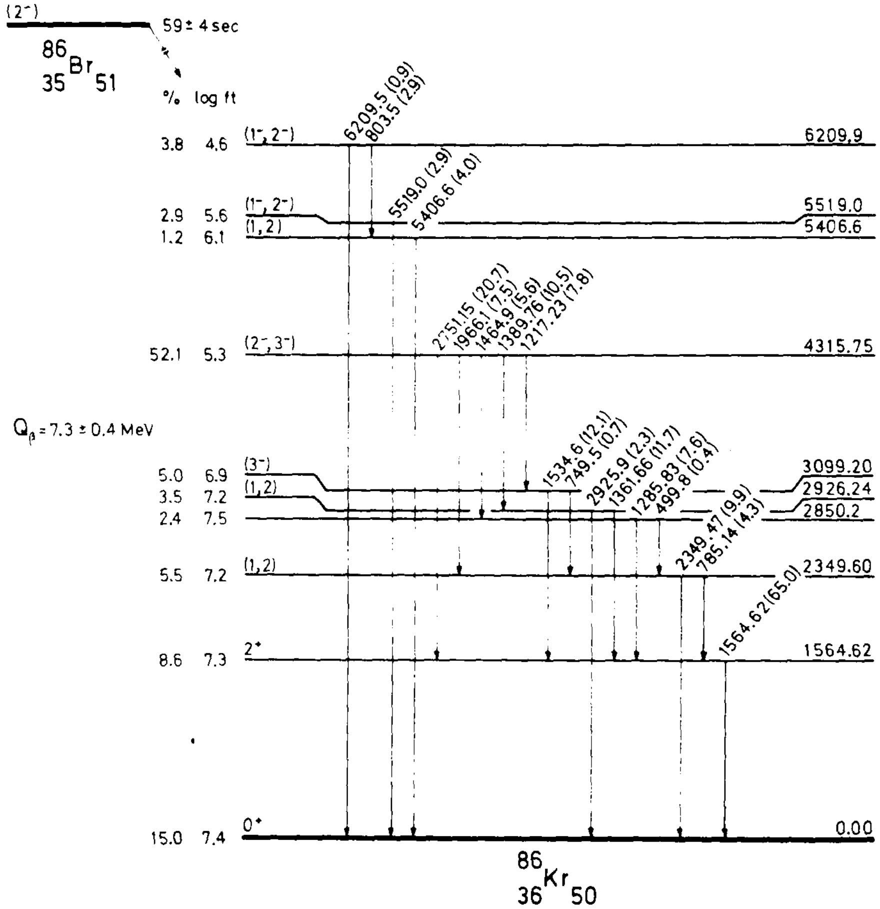

FIG. 2. Level scheme of ^{86}Kr. The γ-ray energies are in keV and the intensities are given per 100 decays. The Q_β value has been taken from Ref. 16 and the intensity of the ground-state β branch from Ref. 2.

mass-86 beam was stopped at a distant and well-shielded position on the moving tape, and collection took place for approximately 160 sec. Then the activity was displaced to a position in front of the detector and eight successive spectra of 20 sec each were recorded. During the measuring time a fresh source was built up and automatically positioned when the last 20-sec spectrum of the previous accumulation had been taken. This procedure was repeated several hundred times in order to obtain acceptable statistics. The spectra were analyzed, and from the peak areas the values of the half-life were obtained by Peierls's method. This could be done with a reasonable error for only 10 γ rays. The positioning of the source takes about 10 sec, and this delay, together with the dynamics of the fission-products transport to the separator ion source probably makes it impossible for us to observe the shorter half-life reported in Ref. 3.

III. RESULTS AND DISCUSSION

Figure 1 shows a part of a typical γ-ray spectrum in which are identified: (a) the peaks corresponding to transitions in ^{86}Kr established as such by the procedure outlined in the preceding section; (b) the peaks used for energy calibration; (c) the contamination lines that contribute to ^{86}Kr peaks, and thus must be taken into account for intensity calculations.

The results of our γ-ray measurements, as well as the values of the half-lives of the transitions for those cases where direct measurements have been performed, are shown in Table I.

19 transitions were positively assigned to ^{86}Kr, in much better general agreement with the results of Ref. 2 than with those of Ref. 3, also entered in Table I. The four rays identified by Lundán[3] as long-lived showed in our experiments the half-life corresponding to ^{86}Br decay. A 5519.0-keV transition which Lundán could not decide if it belonged to mass 86 or 87, was definitely assigned to the former. The 1564.62-keV transition showed a pure half-life within the experimental errors and limitations of the technique used, and no initial growth[3] has been observed in our experiments. From our measurements a value of 59 ± 4 sec for the ^{86}Br ground-state half-life has been obtained. The 749.5- and 785.14-keV transitions most probably correspond to the 0.8-MeV peak observed in Ref. 2 by coincidence experiments.

TABLE II. β feedings to the ^{86}Kr levels.

Level energy	I_β (%)	$\log ft$	$\log f^1t$[a]
0	15.0[b]	7.4	8.4
1564.62 ± 0.09	8.6	7.3	8.1
2349.60 ± 0.14	5.5	7.2	7.9
2850.2 ± 0.4	2.4	7.5	8.0
2926.24 ± 0.13	3.5	7.2	7.8
3099.20 ± 0.16	5.0	6.9	7.4
4315.75 ± 0.17	52.1	5.3	5.6
5406.6 ± 0.5	1.2	6.1	6.2
5519.0 ± 0.9	2.9	5.6	5.6
6209.9 ± 0.5	3.8	4.6	5.0

[a] The possibility of first-forbidden unique transition has been excluded whenever $\log f^1t \leq 7.6$ (Nuclear Data Group criteria).

[b] The intensity of the ground-state β branch has been taken from Ref. 2, and the Q_β value from Ref. 16.

The proposed level scheme, shown in Fig. 2, is based on our energy-sum relations and takes into account the results of (γ, γ) and (β, γ) coincidences published by Williams and Coryell.[2]

The transition of 1768.5 keV is the only one not placed in the level scheme, but it carries only 0.8% of the total γ intensity detected. Levels at 1564.62, 2349.60, 4315.75, and 6209.9 keV agree very well with the ones proposed in Ref. 2 at 1.56, 2.34, 4.32, and 6.18 MeV, respectively. The three levels at 3099.20, 2926.24, and 2850.2 keV, and the two at 5406.6 and 5519.0 keV, correspond to those at 2.92 and 5.44 MeV previously reported in Ref. 2, now separated into components because the better resolution of our γ detector allows us to resolve formerly complex γ peaks

The 1217.23- 1534.6-keV cascade in our level scheme is in good agreement with the coincidence of unknown sequence between 1.2- and 1.5-MeV transitions, proposed in Ref. 2 as deexciting the 4315.75-keV level.

The β feedings have been obtained from the γ-ray intensity balance for each level. Based on these values, on the data given in Ref. 2 for the β branch to the ground state, and on the Q value,[16] $\log ft$ values have been calculated. These values are different from the ones previously calculated by Auble[16] based on the Williams and Coryell data, because in their work several of the peaks were complex and the unresolved intensities incorrectly placed in the level scheme. Table II shows the β branching, the $\log ft$ values, and the energy of the proposed ^{86}Kr levels.

From the present work only the main features of the ^{86}Br decay are well established. In the following discussion we indicate our conclusions on spin and parity assignments to the ^{86}Kr levels.

The ground state of the even-even nucleus ^{86}Kr is 0^+. Nuclear-reaction studies[4,5] have determined $J^\pi = 2^+$ for the first excited level at 1564.62 keV and (3^-) for that at 3099.20 keV. These assignments, when combined with our $\log ft$ values by using the criteria adopted by the Nuclear Data Group, lead to $J^\pi = (2^-)$ for the ^{86}Br ground state.

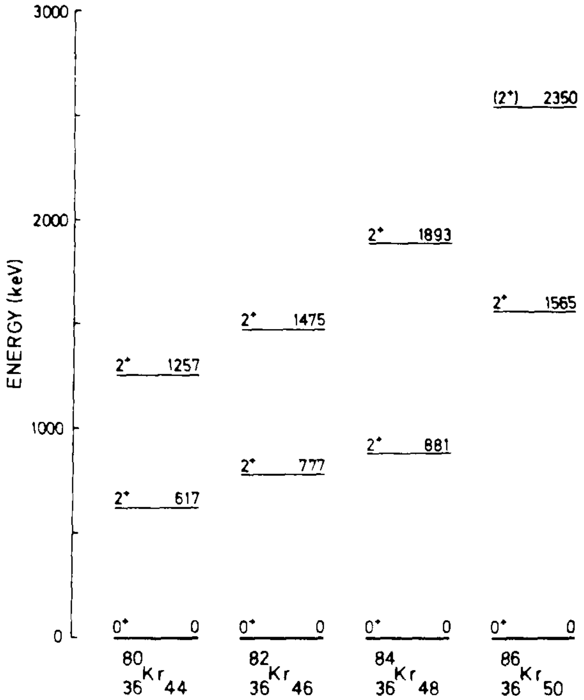

FIG. 3. First and second 2^+ levels in even Kr isotopes.

The parentheses must be kept because of that in the (3^-) assignment. However, the J^π value proposed for the ^{86}Br ground state agrees very well with the shell-model picture of one neutron in a $2d_{5/2}$ orbit outside the $N=50$ closed neutron shell and one proton in a $2p_{3/2}$ orbit, both coupled to 2^-, as in ^{88}Rb.

The level at 2349.60 keV probably has $J=(1, 2)$, in view of the logft value of its β feeding and of the γ branchings from it and the (3^-) level to the ground state and first excited level. A 2^+ level at 2349.60 keV agrees with the general trend of the second 2^+ level in the even Kr isotopes[17] as shown in Fig. 3. On similar grounds the level at 2926.24 keV would also be (1, 2). For the 2850.2-keV level the logft value allows $(0^+, 1^\pm, 2^\pm, 3^\pm, 4^+)$. The β feeding to the 4315.75-keV level has a logft $=5.3$; thus, the J^π assignment for it is $(1^-, 2^-, 3^-)$. However, due to the existence of the transition to the first excited level and the absence of that to the ground state, the most probable spins are 2 or 3.

For the levels at 5406.6, 5519.0, and 6209.9 keV, the logft values indicate J^π values of, respectively, (1, 2, 3), $(1^-, 2^-, 3^-)$, and $(1^-, 2^-, 3^-)$, but the existence of γ transitions to the ground state and the absence of those to the first excited level most probably rule out the $J=3$ assignments.

We have not been able to observe the 4^+ level theoretically predicted at 1.74 MeV,[18] probably due to the weakness of the β feeding from the ^{86}Br ground state.

It might be appropriate to emphasize the need of nuclear-reaction studies in order to improve the knowledge of the level structure in ^{86}Kr.

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[1] A. F. Stehney and E. P. Steinberg, Phys. Rev. 127, 563 (1962).

[2] E. T. Williams and C. D. Coryell, Phys. Rev. 144, 945 (1966).

[3] A. Lundán, Z. Physik 230, 403 (1970).

[4] C. L. Hollas, H. R. Hiddleston, V. D. Mistry, and P. J. Riley, in *Nuclear Isospin*, edited by G. D. Anderson, S. D. Bloom, J. Cerny, and W. W. True (Academic, New York, 1969), p. 667.

[5] B. Rosner and E. J. Schneid, Nucl. Phys. 82, 182 (1966).

[6] E. Achterberg, F. C. Iglesias, A. E. Jech, A. Kasulin, E. Kerner, J. Mónico, J. A. Moragues, D. Otero, M. L. Pérez, M. Pinamonti, A. N. Proto, R. Requejo, J. J. Rossi, W. Scheuer, and J. F. Suárez, to be published.

[7] T. Inouye, T. Harper, and N. C. Rasmussen, Nucl. Instr. Methods 67, 125 (1969).

[8] J. T. Routti and S. G. Prussin, Nucl. Instr. Methods 72, 125 (1969).

[9] IALE project, to be published.

[10] G. A. Bartholomew, A. Doveika, K. M. Eastwood, S. Monaro, L. V. Groshev, A. M. Demidov, V. I. Pelekhov, and L. L. Sokolovskii, Nucl. Data A3, 367 (1967).

[11] Values adopted from: A. Fubini, M. Giannini, E. Ivanov, M. Popa, D. Prosperi, and V. Rado, in *Neutron Capture Gamma-Ray Spectroscopy* (International Atomic Energy Agency, Vienna, Austria, 1969), p. 317; J. J. Reidy and M. L. Wiedenbeck, Nucl. Phys. 70, 518 (1965); W. John and R. W. Jewell, ANL Report No. ANL-6797, 1963 (unpublished), p. 143.

[12] J. B. Marion, Nucl. Data A4, 301 (1971).

[13] F. K. Wohn, W. L. Talbert, Jr., and J. K. Halbig, Nucl. Phys. A152, 561 (1970).

[14] A. Shihab-Eldin, S. G. Prussin, F. M. Bernthal, and J. O. Rasmussen, Nucl. Phys. A160, 33 (1971).

[15] IALE project, to be published.

[16] R. L. Auble, Nucl. Data B5, (No. 2), 151 (1971)

[17] D. G. McCauley and J. E. Draper, Phys. Rev. C 4, 475 (1971).

[18] V. Gillet, B. Giraud, J. Picard, and M. Rho, Phys. Letters 27B, 483 (1971).