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Applied Radiation and Isotopes 55 (2001) 477–483

Applied Radiation and Isotopes

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Energy levels in ^{139}La from the decay of ^{139}Ba

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Received 14 February 2001; accepted 18 April 2001

Abstract

The γ-ray spectrum of ^{139}La following the β^- decay of ^{139}Ba has been studied using both singles and $\gamma\gamma$ coincidence spectroscopy techniques. The energies and intensities of 30 γ-transitions have been determined, which include three new transitions placed in the level scheme. Two new levels at 1524.6 and 1900.3 keV excitation energies are proposed and a number of γ-transitions have been confirmed. On the basis of these results a precise decay scheme is proposed.

1. Introduction

In the last years, the excited energy levels in ^{139}La has been investigated through the ^{139}Ba EC and β^- decays and with different nuclear reactions, in connection with theoretical calculations, but the experimental results are not consistent with the theoretical predictions. Kisslinger and Sorensen (1963) have made shell model calculations with pairing interaction and their results yield the low lying levels with $J^\pi = 7/2^+$ (ground state) and $5/2^+$ (first excited state). Lombard (1968), using the BCS shell-model, has also predicted these two low-lying levels, but no other levels are predicted at higher excitation energies, up to about 1 MeV. Freed and Miles (1968) have calculated the expected energy level spectrum of ^{139}La from the coupling of quadrupole phonons with the $g_{7/2}$ and $d_{5/2}$ proton, using the intermediate coupling version of the unified model. They have predicted six states between 1.0 and 1.5 MeV. The unified model has been applied by Waroquier and Heyde (1970) and by Szichman et al. (1970) too, and new levels were calculated up to about 1.2 MeV excitation. Although theory predicts no levels between 200 keV and 1.0 MeV for ^{139}La, several experimental works have reported levels and γ-transitions in this energy region. These include results of Coulomb excitation, performed by Kulkari and Andhradev (1979), and inelastic neutron scattering measurements, carried out by Bukarev and Popov (1965), Wilenzick and Palms (1966) and, more recently, by Ubbondanno et al. (1987). From the studies of the levels populated through the EC/β^+ and β^- decay (Burrows, 1989), little information is established because in the ^{139}Cs decay the disintegration energy, Q_{EC}, is about 270 keV only, and the absence of experimental information from ^{139}Ba decay is mainly due to the fact that approximately 99% of its β^- decay populates the ground and first excited states, the remaining $\sim$1% populating higher excited states, up to about 2.1 MeV. Basically, the results of two studies performed by Hill and Wiedenbeck (1968), and by Berzins et al. (1969), established the features of the β^- decay scheme of ^{139}Ba. According to the last compilation by Burrows (1989), the latest paper involving the ^{139}Ba β^- decay was that of Faller et al. (1986), but the level scheme proposed is essentially the same of the study by Berzins et al. (1969), with one additional level at 1209 keV previously suggested by Wildenthal et al. (1971) in a proton-transfer reaction.

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0969-8043/01/$ - see front matter
PII: S0969-8043(01)00105-1

The purpose of this work is to investigate the states in ^{139}La through the ^{139}Ba β^- decay, to obtain complementary experimental information on the population of low-lying levels (below 2 MeV).

The present work is concerned with a precise measurement of energies, intensities and coincidence relations among the electromagnetic transitions in ^{139}La, fed through the β^- decay of ^{139}Ba. This includes an extensive γ-ray measurement, using high resolution detectors, with high counting statistics in the region from 70 keV up to 2.2 MeV.

2. Experimental procedure

2.1. Source preparation

The radioactive sources of ^{139}Ba ($T_{1/2} = 84.6$ min) were obtained from the $^{138}Ba(n,\gamma)^{139}Ba$ reaction. Approximately 10 mg of natural barium in the form of $Ba(NO_3)_2$ were irradiated in a thermal neutron flux of 5×10^{13} n/cm^2 s for different periods, from 3 to 15 min, in the IEA-R1 reactor at IPEN-CNEN/SP in São Paulo. After irradiation, the source was dissolved in a couple of drops of water and transferred to a lucite container, which was then mounted at the center of the γ-spectrometer for measurement. The source to detector distance was 15 cm. Before starting the measurements, the source was let cool down for a period of 60 min, to allow for the decay of short-lived activities of $^{131}Ba^m$ ($T_{1/2} = 14.6$ min) and $^{137}Ba^m$ ($T_{1/2} = 2.6$ min), also formed during the irradiation. Each radioactive source was counted for a period of 4 h, after which the interference of the longer-lived activity of ^{131}Ba ($T_{1/2} = 11$ d) became significant.

Neutron activation analysis was employed to determine the impurities in the $Ba(NO_3)_2$ sample used in the experiment. For this analysis, the sample was irradiated for different periods (from few minutes to hours) in a thermal neutron flux in the IEA-R1 reactor. This was done in order to allow the identification of long- and short-lived nuclides produced from trace impurities in the source. The impurities identified were aluminum and manganese, observed through the production of ^{28}Al ($T_{1/2} = 2.3$ min) and ^{56}Mn ($T_{1/2} = 2.6$ h), respectively. This analysis is described in detail in the work performed by Zamboni et al. (1997).

2.2. γ-ray measurements

The singles spectra were studied with the help of two independent spectrometer systems, consisting of a 75 cm^3 HPGe and a 35 cm^3 Ge(Li) coaxial detectors, respectively. The HPGe energy resolution was 1.9 keV at 1.33 MeV and that of the Ge(Li) was 1.8 keV at 0.66 MeV. Both systems were operated with ORTEC 572 amplifiers, in pile-up rejection mode. The HPGe spectrometer system was mounted inside an iron shield, described by Camargo et al. (1998), in order to reduce the background radiation. Photon energies from 70 keV to 2.5 MeV were investigated with this system. The energies and relative intensities of all γ-rays were measured with no absorber. The γ-spectrum from 70 keV up to 1.0 MeV was also observed with the Ge(Li) detector in association with a BGO Compton-suppression system, but no intensity measurements were made. This was done to check for the presence of γ-transitions in this energy region, as suggested in several nuclear reaction studies (Burrows, 1989).

2.3. $\gamma\gamma$ coincidence spectra

Two $\gamma\gamma$ coincidence experiments were carried out. In the first one, a 90 cm^3 HPGe detector was used in association with a 45 cm^3 Ge(Li), both with an energy resolution better than 2.0 keV at 1.3 MeV. A conventional fast-slow coincidence circuit, with time resolution of 11 ns has been used. Two equally sized hardware gates were set on the timing spectrum, to tag the coincidence events either as "true + chance" or "chance". At every master gate three parameters were recorded (the deposited energy in both detectors and the coincidence tag) with the help of a CAMAC input register, assisted by an MBD-11 microprocessor, connected to a PDP-11/84 computer. The method of analysis was the same as described by Brown and Roulston (1969). The counting time for this experiment was 100 h.

In the second experiment, a 75 cm^3 HPGe detector was used in association with a 7.6 cm $\times$ 7.6 cm NaI(Tl). The $\gamma\gamma$ coincidences were recorded using a low-noise fast coincidence system and a pulse height analyzer. The photopeak at 166 keV, as seen through the NaI(Tl) detector, was selected in a single-channel analyzer (SCA). The intensities of γ-ray coincidences were determined from the HPGe detector. An additional gate, on the higher energy side of the main gate at 166 keV, served to determine the interference of Compton scattered radiation of higher-energy γ-rays in the window setting. The chance coincidences were determined in a separate experiment, by introducing a 1 μs delay in the fast electronics line of one of the detectors before the coincidence unit, and recording the coincidence spectrum. In both experiments the detectors were placed at 130° and a 0.5 cm Pb absorber was used in front of the HPGe detector, to reduce the intensity of the strong 166 keV γ-ray. The counting time for this $\gamma\gamma$ coincidence experiment was about 60 h.

3. Experimental results and discussion

The singles spectrum from about 70 keV to 2.2 MeV, recorded with the HPGe detector during 130 h of live time counting, is shown in Figs. 1–4. Thirty transitions were attributed to the β^- decay of ^{139}Ba. The measured γ-ray energies and relative intensities are listed in Table 1, and compared with data from Hill and Wiedenbeck (1968), and Berzins et al. (1969). Three transitions with energies 268.27, 1524.65 and 1900.33 keV were observed for the first time and two new levels at 1524.8 and 1900.3 keV have been established. The 1042.9 keV transition suggested solely by Faller et al. (1986), and the 1518 keV transition suggested solely by Berzins et al. (1969), were not confirmed. Upper limits for their intensities were calculated following Helene's prescription (Helene, 1983) for a 95% confidence level, and are presented in Table 1, showing that this experiment has achieved a better overall sensitivity. A weak γ-ray, at 1894.7 keV, has been suggested by Hill and Wiedenbeck (1968), but according to those authors the existence of this peak is considered to be uncertain, since its statistics was very poor. We examined the region around 1900 keV, in our spectra, but no evidence was found confirming its presence. Its upper limit was calculated as well, and it is presented in Table 1.

According to our coincidence data, the results were conclusive only for the 166 keV gate, since the statistics was very poor for the other gates. The transitions at 268*, 1054, 1091, 1215, 1254, 1310, 1370, 1392*, 1595, 1600, 1690*, 1754* and 1796* keV were observed in coincidence with the 166 keV transition (transitions marked with an asterisk were observed only with the HPGe–Ge(Li) detector combination). These coincidence relationships allowed us to confirm the levels at 166, 1219, 1257, 1381, 1420, 1476, 1536, 1558, 1578, 1683, 1762, 1766, 1857, 1920, 1962 and 2061 keV in the β^- decay scheme. However, the level at 1209 keV, previously suggested by Wildenthal et al. (1971), through a proton transfer reaction and by Faller et al. (1986), from beta decay, depopulated through the 1043 keV transition, could not be placed in the current decay scheme of ^{139}Ba, since this photopeak is not observed in

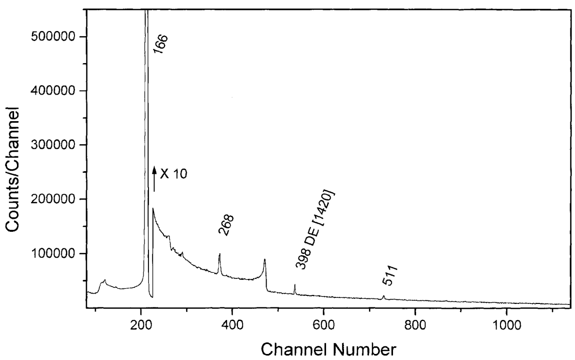

Fig. 1. γ-ray singles spectrum of ^{139}Ba (channels 80–1170). Energies are given in keV.

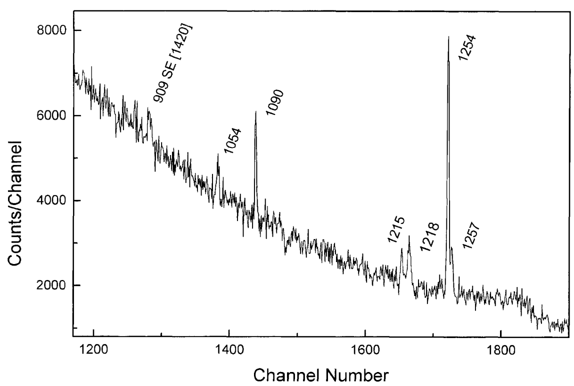

Fig. 2. γ-ray singles spectrum of ^{139}Ba (channels 1170–1900). Energies are given in keV.

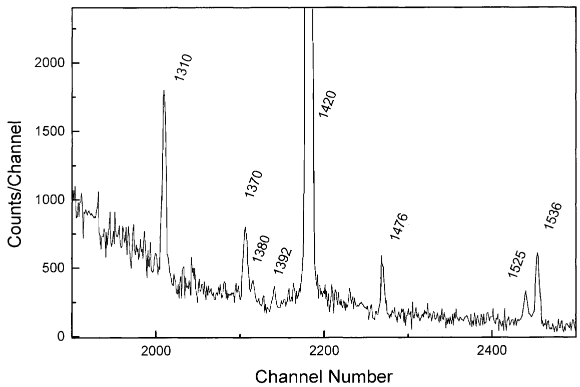

Fig. 3. γ-ray singles spectrum of ^{139}Ba (channels 1900–2500). Energies are given in keV.

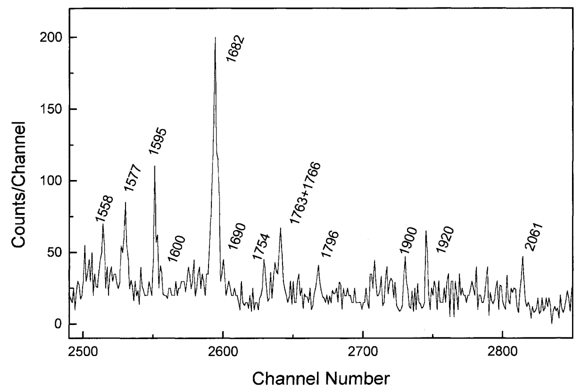

Fig. 4. γ-ray singles spectrum of ^{139}Ba (channels 2490–2900). Energies are given in keV.

Table 1
Energy (E_γ) and relative intensity (I_γ) of the γ-rays following the ^{139}Ba decay

This work *Natural barium* (No absorber) E_γ (keV) I_γ (%)[a]	Berzins et al. *Natural barium* (5 mm Cd–Pb absorber) E_γ (keV) I_γ (%)[a]	Hill and Wiedenbeck 99.8% ^{138}Ba (0.32 cm Pb absorber) E_γ (keV) I_γ (%)[a]
165.96 (5)	165.8	165.85 (2)
8335 (149)	7300	6230 (900)
268.27 (7)	—	—
2.10 (18)	—	—
1042.9[b]	—	—
0.01[b] < 0.0005[c]	—	—
1053.83 (8)	1052.9 (5)	1053.0 (5)
0.1968 (6)	0.12	0.33 (10)
1090.71 (4)	1090.9 (3)	1090.8 (2)
4.361 (1)	3.1	6.2 (4)
1215.31 (8)	1215.5 (5)	1215.5 (4)
1.223 (2)	1.2	1.35 (35)
1218.81 (15)	1219.1 (5)	1219.1 (4)
1.7676 (3)	1.5	1.9 (4)
1254.36 (12)	1254.8 (3)	1254.7 (2)
11.476 (16)	10	15.5 (6)
1256.66 (2)	1256.7 (10)	—
1.331 (2)	1.7 1.03(12)[d]	—
1310.37 (2)	1310.6 (3)	1310.6 (2)
5.598 (10)	5.4	6.1 (3)
1370.25 (2)	1370.6 (5)	1370.5 (3)
1.049 (3)	1.1	1.13 (11)
1380.80 (2)	1382 (1)	1381.5 (5)
0.0940 (3)	0.03	0.11 (6)
1392.117 (6)	1393 (1)	1392.4 (5)
0.0654 (2)	0.03	0.06 (4)
1420.19 (10)	1420.5 (3)	1420.5 (2)
100[a]	100	100
1476.09 (9)	1476.6 (5)	1476.3 (3)
0.669 (3)	0.61	0.63 (5)
—	1518 (1)	—
< 0.0010[c]	0.02	—
1524.65 (18)	—	—
0.0770 (5)	—	—
1536.02 (9)	1536.3 (5)	1536.3 (3)
0.965 (6)	1.0	0.81 (6)
1558.31 (32)	1558.5 (5)	1558.2 (4)
0.1203 (8)	0.09	0.078 (30)
1577.83 (39)	1578.3 (5)	1578.2 (4)
0.259 (2)	0.2	0.20 (5)
1594.95 (11)	1595.7 (3)	1595.3 (3)
0.867 (7)	0.93	0.79 (6)
1600.39 (21)	1601.4 (10)	—
0.137 (1)	0.08 0.05(1)[d]	—
1682.81 (4)	1683.4 (5)	1683.1 (3)
1.183 (12)	1.2	0.98 (5)
1690.51 (6)	1691.2 (10)	—
0.0879 (9)	0.09 0.11(1)[d]	—
1754.68 (16)	1755 (1)	1754.5 (5)
0.0391 (5)	0.02	0.033 (17)
1762.72 (8)	1762 (1)	—

Table 1 (*continued*)

This work *Natural barium* (No absorber) E_γ (keV) I_γ (%)[a]	Berzins et al. *Natural barium* (5 mm Cd–Pb absorber) E_γ (keV) I_γ (%)[a]	Hill and Wiedenbeck 99.8% ^{138}Ba (0.32 cm Pb absorber) E_γ (keV) I_γ (%)[a]
0.0329 (4)	0.02 0.03(1)[d]	—
—	—	1765.5 (4)
—	—	0.066 (25)
1766.00 (7)	1767.6 (10)	—
0.0898 (12)	0.1	—
1796.35 (5)	1797.4 (10)	—
0.0408 (7)	0.03 0.02(1)[d]	—
—	1896 (1)	1894.7 (7)[e]
<0.008[c]	0.02	0.008 (6)
1900.23 (27)	—	—
0.0438 (7)	—	—
1920.21 (13)	1922 (1)	1920.6 (4)
0.061 (12)	0.04	0.030 (14)
2061.22 (35)	2061 (1)	2060.1 (4)
0.0226 (5)	0.05	0.019 (9)

[a] Intensities normalized to 100% for the 1420-keV transition.
[b] Extracted from Faller et al. (1986). According to the authors, the experimental uncertainty value was due to chance coincidences.
[c] A transition with intensity larger than the quoted value has 95% probability of detection in our spectra but was not observed.
[d] Extracted from Laird (1978). According to the authors no energy value was reported and the energies values are those from Berzins et al. (1969).
[e] Energy obtained from a weighted average of singles and coincidence measurements.

our singles spectra, and the analysis of the 166 keV gate revealed no evidence of coincidence between the 166 and 1043 keV transitions.

According to Berzins et al. (1969), the 1683 keV state is de-excited through the emission of two γ-rays, of energies 1518 and 1683 keV. The 1518 keV photopeak is not present in our singles spectra and it is not observed in coincidence with the 166 keV transition as well. We thus set an upper limit for its presence in our data (see Table 1) and do not place it in the proposed level scheme. Differently, the 1682.81 keV transition is observed in our singles spectrum, but it is not in coincidence with 166 keV γ-ray. It is then placed as a transition leading directly to the ground state, allowing for the confirmation of a level at 1682.82 keV.

The 1524.79 and 1990.34 keV levels were proposed based on the observation the 1524.65 and 1900.23 keV transitions, respectively. Further, on the basis of the energy sums of the 1256.66 and 268.27 keV transitions, we suggest that the 268 keV transition could be placed in the current decay scheme depopulating the new level at 1524.79 keV.

3.1. Decay scheme

Considering that the ground states of ^{139}La and ^{139}Ba are established as having $J^\pi = 7/2^+$ and $7/2^-$, respectively (Burrows, 1989), the excited levels in ^{139}La will have spin values ranging from 3/2 to 11/2, but the 11/2 assignment is ruled out for the levels decaying to the 166 keV level, which has $J^\pi = 5/2^+$. Besides, according to the log ft values and the β- and γ-transition selection rules, the majority of the states are consistent with positive parity, except for the 1420 keV level, which has a low log ft value, 7.6. The ^{139}Ba decay scheme consistent with these measurements is shown in Fig. 5. The spin assignments were based on the present log ft values, calculated according to Gove and Martin (1971) and on the observed decay modes and nuclear reaction assignments (Burrows, 1989). The 72% intensity of the β^- feeding to the ^{139}La ground state and the Q_β-value ($Q_\beta = 2306$ keV) were taken from the Nuclear Data Sheets (Burrows, 1989). The intensities of the other β feedings were obtained from the intensity balance of the transitions which enter and leave the levels. The energies of the levels were obtained through a least-squares fit, using all transitions that could be placed in the decay scheme. The results for the level energies and β feedings are presented in Table 2. The data from Berzins et al. (1969), Hill and Wiedenbeck (1968), and from the last compilation by Burrows (1989) were also included for comparison.

The scheme of ^{139}La obtained from the present work is compared with other works (Burrows, 1989) and our

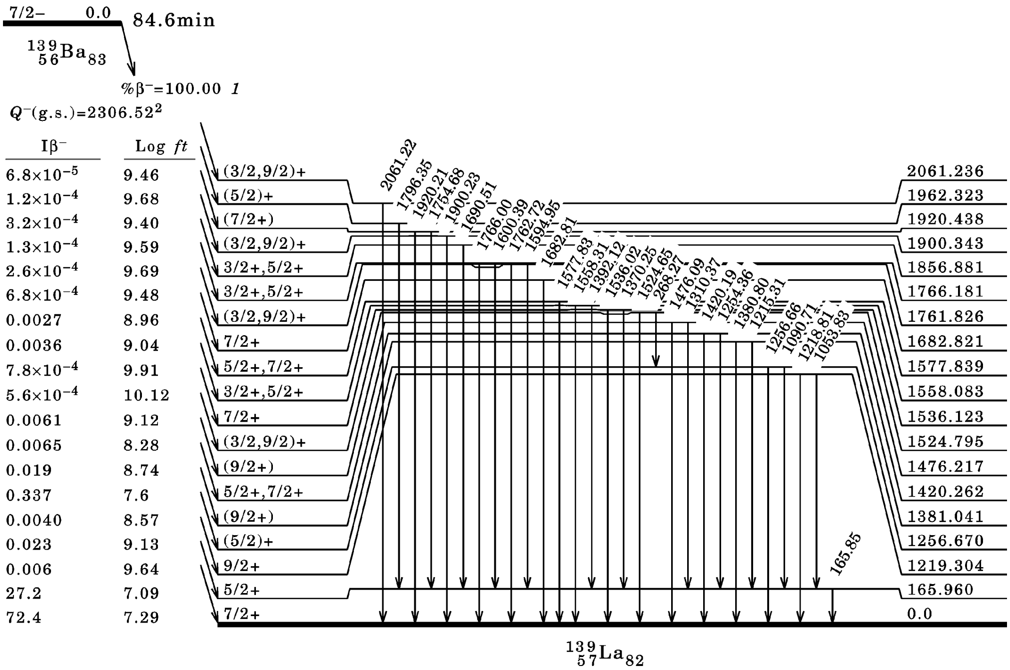

Fig. 5. ^{139}Ba disintegration scheme from this work.

Table 2
^{139}La energy levels and β^- intensities from ^{139}Ba decay

This work	Berzins et al.	Hill and Wiedenbeck	Burrows
Energy levels (keV) I_{β^-} (%)	Energy levels (keV) I_{β^-} (%)	Energy levels (keV) I_{β^-} (%)	Energy levels (keV) I_{β^-} (%)
2061.236 (35)	2061	2061.1	2060.5
0.000068	0.00021	0.00011	0.00007
1962.323 (7)	1963	—	1962.9
0.00012	0.000087	—	0.00005
1920.438 (21)	1922	1920.6	1920.74
0.00032	0.00017	0.00026	0.00013
1900.343 (27)	—	—	—
0.00013	—	—	—
1856.881 (78)	1857	—	1856.3
0.00026	0.00027	—	0.00029
1766.181 (96)	1767.8	1765.5	1766.25
0.00068	0.00055	0.00027	0.00030
1761.826 (42)	1762	1761.1	1761.2
0.0027	0.0029	0.0032	0.0021
1682.821 (40)	1683.4	1683.1	1683.4
0.0036	0.0037	0.0040	0.0026
1577.839 (39)	1578.3	1578.2	1578.04
0.00078	0.00061	0.00081	0.00052
1558.083 (33)	1558.5	1558.2	1558.39
0.00056	0.00039	0.00056	0.00028
1536.123 (19)	1536.3	1536.3	1537.87
0.0061	0.0064	0.0078	0.0051

Table 2 (*continued*)

This work	Berzins et al.	Hill and Wiedenbeck	Burrows
Energy levels (keV) I_{β^-} (%)	Energy levels (keV) I_{β^-} (%)	Energy levels (keV) I_{β^-} (%)	Energy levels (keV) I_{β^-} (%)
1524.795 (19)	—	—	—
0.0065	—	—	—
1476.217 (11)	1476.6	1476.4	1476.3
0.019	0.018	0.027	0.0175
1420.262 (10)	1420.5	1420.5	1420.54
0.337	0.34	0.47	0.287
1381.041 (9)	1382	1381.3	1381.30
0.0040	0.0038	0.0059	0.0032
1256.670 (76)	1256.7	—	1256.83
0.023	0.015	—	0.0108
1219.304 (26)	1218.9	1219.1	1218.96
0.006	0.0050	0.0090	0.0042
—	—	—	1209.0
—	—	—	—
165.960 (5)	165.84	165.8	165.864
27.2	27.2	27	29.68

results are consistent, in part, with those published by Hill and Wiedenbeck (1968), and with Berzins et al. (1969), but the energy levels and γ-ray energies were given more accurated values. Besides, the excited levels in the range 1.1–2.0 MeV proposed earlier (Burrows, 1989) have been confirmed. We also observe a new transition at 268 keV placed in the beta decay scheme as depopulating a new level at 1525 keV, to the well-known level at 1257 keV excitation energy, but no evidence was found for levels between 170 and 1200 keV.

We believe that the data from the present study offer an opportunity for future calculations that might attempt to describe the low-lying states in ^{139}La.

Acknowledgements

The authors acknowledge the financial support from FAPESP, CNPq and CAPES.

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