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LEVELS IN THE $N = 82$ NUCLEUS ^{139}La POPULATED IN ^{139}Ba DECAY

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Abstract: The decay of ^{139}Ba to levels in ^{139}La was investigated using Ge(Li) gamma-ray detectors. On the basis of energy, intensity and coincidence measurements, a new decay scheme is proposed. In addition to well-known levels at 166 and 1420 keV, 12 new levels between 1200 and 2100 keV were observed. The results are compared with those for other odd-mass $N = 82$ isotones.

E | RADIOACTIVITY ^{139}Ba [from ^{138}Ba(n, γ)]; measured E_γ, I_γ, $\gamma\gamma$-coin. ^{139}La deduced levels, log *ft*. Enriched target Ge(Li) detector.

1. Introduction

The levels of ^{139}La have been studied through the decay [1-4]) of ^{139}Ba and through various nuclear reactions [5-7]). Decay studies have firmly established only two levels at 166 and 1420 keV. This work was carried out as part of a program to elucidate the level structure of the $N = 82$ isotones. Singles and coincidence gamma-ray spectra were measured with the aid of high-resolution Ge(Li) spectrometers.

2. Source preparation

Several mg of $Ba(NO_3)_2$ enriched to 99.8 % in ^{138}Ba were irradiated with a thermal neutron flux of 2×10^{13} n/cm^2 · sec in the University of Michigan Ford Reactor. Typical irradiations lasted about 4 h. The barium was chemically purified by three precipitations as $BaCl_2$ from a cold 1 : 4 mixture of ether and HCl. The procedure used was similar to that of Sunderman and Townley [8]). The time from reactor to counting was about 90 min. The only source impurities encountered were ^{24}Na and an unidentified long-lived gamma ray at about 1690 keV. These impurities were evident only for counting periods longer than 200 min.

3. Gamma-ray energies and intensities

The gamma spectrum was measured with a Ge(Li) trapezoidal detector having an active volume of 40 cm^3. The resolution width (FWHM) obtained for the 1332 keV

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gamma ray from ^{60}Co was 2.9 keV. Typical gamma spectra for ^{139}Ba are shown in figs. 1 and 2. A 0.32 cm Pb absorber was used to reduce the intensity of the strong 166 keV gamma ray. A spectrum measured in the absence of the Pb absorber revealed no new gamma rays at energies below 400 keV. No effects due to coincidence summing were observed. All gamma rays ascribed to ^{139}Ba decay were found to have the correct half-life [9]) of 82.9 min with the exception of the weak gamma rays at 1053, 1382, 1392 and 1895 keV. The half-life for the first two was correct, but statistics were

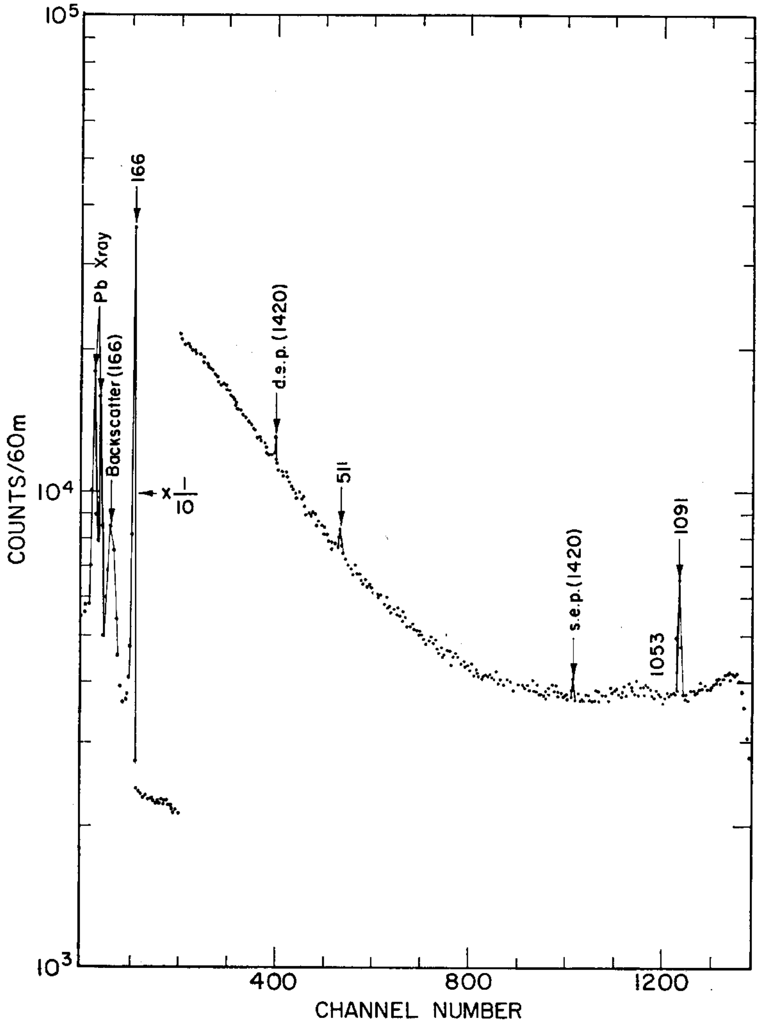

Fig. 1. The pulse-height spectrum of gamma radiation between 50 and 1200 keV accompanying the decay of ^{139}Ba. A 0.32 cm Pb absorber was used. The symbols s.e.p. and d.e.p. refer to single and double escape peaks, respectively. All energies are in keV.

poor. It was not possible because of poor statistics to obtain a half-life for the latter two.

The energies of all gamma rays above 1000 keV were measured with the Ge(Li) detector. Standard lines [10]) from ^{207}Bi, ^{65}Zn, ^{60}Co, ^{22}Na and ^{88}Y were used as

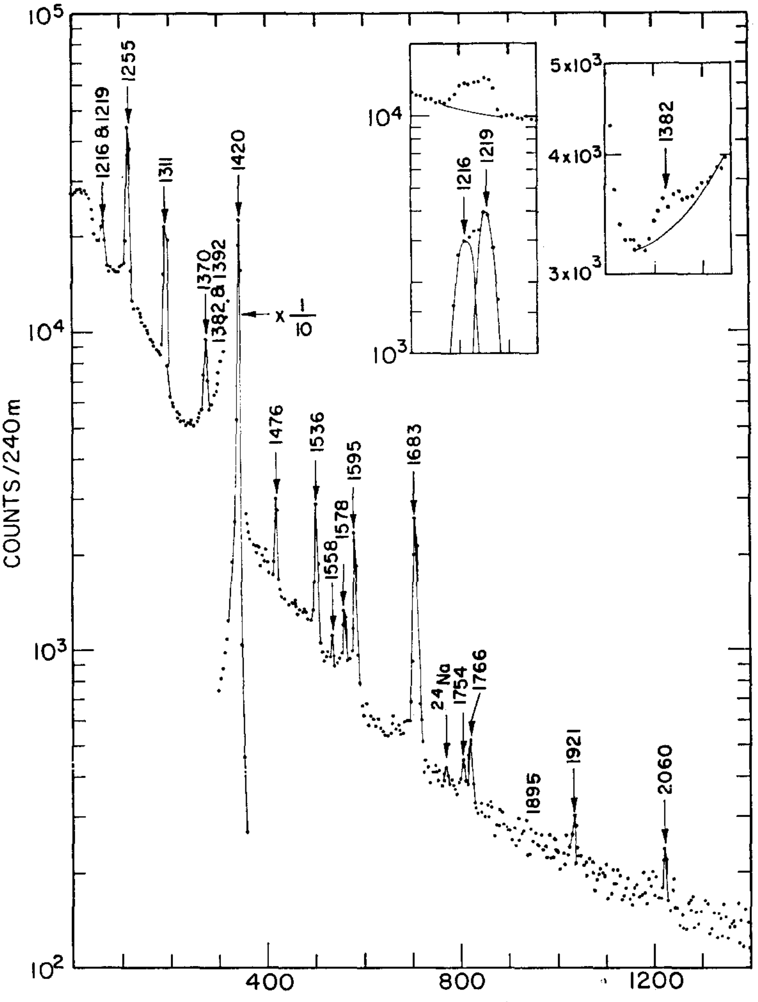

Fig. 2. The pulse-height spectrum of gamma radiation between 1200 and 2100 keV accompanying the decay of ^{139}Ba. A 0.32 cm Pb absorber was used. All energies are in keV.

calibration points. Energies of weak gamma rays were obtained using strong gamma rays from ^{139}Ba as secondary standards. The energies and errors of all gamma rays were determined as in earlier work [11]) and are given in table 1. Linearity corrections were determined using the procedure of Donnelly *et al.* [12]). Energies were obtained with a minimum error of 0.2 keV. The energy of the strong 166 keV gamma ray was measured by Baer [13] at this laboratory using the 2 m curved-crystal spectrometer with a Ge(0$\bar{2}$2) crystal.

TABLE 1

Gamma-ray energies and relative intensities

Energy (keV)	Relative intensity [d]
165.85 ±0.02 [a]	6230 ±900
1053.0 ±0.5 [c]	0.33 ± 0.10
1090.8 ±0.2 [b]	6.2 ± 0.4
1215.5 ±0.4 [c]	1.35 ± 0.35
1219.1 ±0.4 [b]	1.9 ± 0.4
1254.7 ±0.2 [b]	15.5 ± 0.6
1310.6 ±0.2 [b]	6.1 ± 0.3
1370.5 ±0.3 [b]	1.13 ± 0.11
1381.5 ±0.5 [b]	0.11 ± 0.06
1392.4 ±0.5 [c]	0.06 ± 0.04
1420.5 ±0.2 [b]	100
1476.3 ±0.3 [b]	0.63 ± 0.05
1536.3 ±0.3 [b]	0.81 ± 0.06
1558.2 ±0.4 [b]	0.078± 0.030
1578.2 ±0.4 [b]	0.20 ± 0.05
1595.3 ±0.3 [b]	0.79 ± 0.06
1683.1 ±0.3 [b]	0.98 ± 0.05
1754.5 ±0.5 [c]	0.033± 0.017
1765.5 ±0.4 [b]	0.066± 0.025
1894.7 ±0.7 [c]	0.008± 0.006
1920.6 ±0.4 [b]	0.030± 0.014
2060.1 ±0.4 [b]	0.019± 0.009

[a] Energy measured using curved-crystal spectrometer.
[b] Energy measured using Ge(Li) spectrometer.
[c] Energy from weighted average of singles and coincidence measurements.
[d] Intensities normalized to 100 for the 1420 keV gamma ray.

Relative gamma intensities were determined from full-energy peaks observed using a 8 cm^2 by 5 mm Ge(Li) detector. The intensity and its error were determined by methods used in earlier work [11]. The efficiency as a function of energy has been determined for our detector by Donnelly *et al.* [12]. The intensity of the 1370 keV gamma ray has been corrected for a 5 % contamination from the 1369 keV line in ^{24}Na. Large uncertainties in certain gamma rays are due to poor statistics.

A search was made for gamma rays at 290, 494, 788 and 950 keV postulated by Jastrzebski [2]. No evidence was observed for gamma rays between 170 and 1050 keV. Upper limits for the intensities of the above four gamma rays are given in table 2. These limits are typical for any gamma ray in this energy region. Upper limits were also placed on the intensities of gamma rays above 1000 keV that might depopulate levels above 1200 keV. Limits for the 1257 and 1761 keV transitions are based on singles measurements while the rest are based on coincidence measurements. The upper limit for the 1257 keV gamma ray is especially large due to its close proximity to the 1255 keV gamma ray.

Inspection of a line at about 1217 keV showed it to be a doublet composed of gamma rays at 1216 and 1219 keV. It is shown in detail in the inset in fig. 2. The relatively large errors for the energies and intensities represent uncertainty in the unfolding procedure. While setting upper limits for intensities of gamma rays above 1000 keV, we became convinced of the existence of weak gamma transitions at 1053, 1382, 1392 and 1895 keV. Coincidence measurements discussed in sect. 4 verified the presence of the 1053 and 1392 keV gamma rays. The 1382 keV gamma ray sits on the low-energy tail of the strong 1420 keV gamma ray. It is shown in detail in the inset in fig. 2.

TABLE 2

Upper limits for various gamma transitions

Energy (keV)	Upper limit intensity [d]
290 [a]	1.8
494 [a]	0.8
788 [a]	0.3
950 [a]	0.2
1257 [b]	1.2
1412 [b,c]	0.03
1517 [b,c]	0.01
1600 [b,c]	0.06
1761 [b]	0.009

[a] Reported in ref. [2]).

[b] Missing transition between levels in our decay scheme.

[c] Upper limit from coincidence measurements.

[d] Intensity relative to 100 for 1420 keV gamma ray.

Energies for the 1053, 1382 and 1392 keV gamma rays were obtained from a weighed average of a minimum of three values obtained from singles and in the case of the 1053 and 1392 keV gamma rays from coincidence measurements. The spread of energy values for these particular gamma rays was never greater than 0.6 keV, and the energy value expected from well-established levels in the decay scheme was always within the energy spread. The 1895 keV gamma ray was observed in both singles and coincidence runs, but the statistics were marginal and the spread of energy values from all runs was 1.5 keV. The existence of the 1895 keV gamma ray is thus considered to be uncertain.

4. Gamma-gamma coincidence measurements

Gamma-gamma coincidence studies were performed using a 7.6 cm × 7.6 cm NaI(Tl) detector and Ge(Li) detectors. The gating pulse for the multi-channel analyser was always obtained from the NaI detector.

The spectrum observed in coincidence with the 166 keV gamma ray is shown in fig. 3. A 32 cm^3 coaxial Ge(Li) detector was used. The detectors were oriented at 180° to each other, and a 0.32 cm Pb absorber was used to reduce the intensity of the

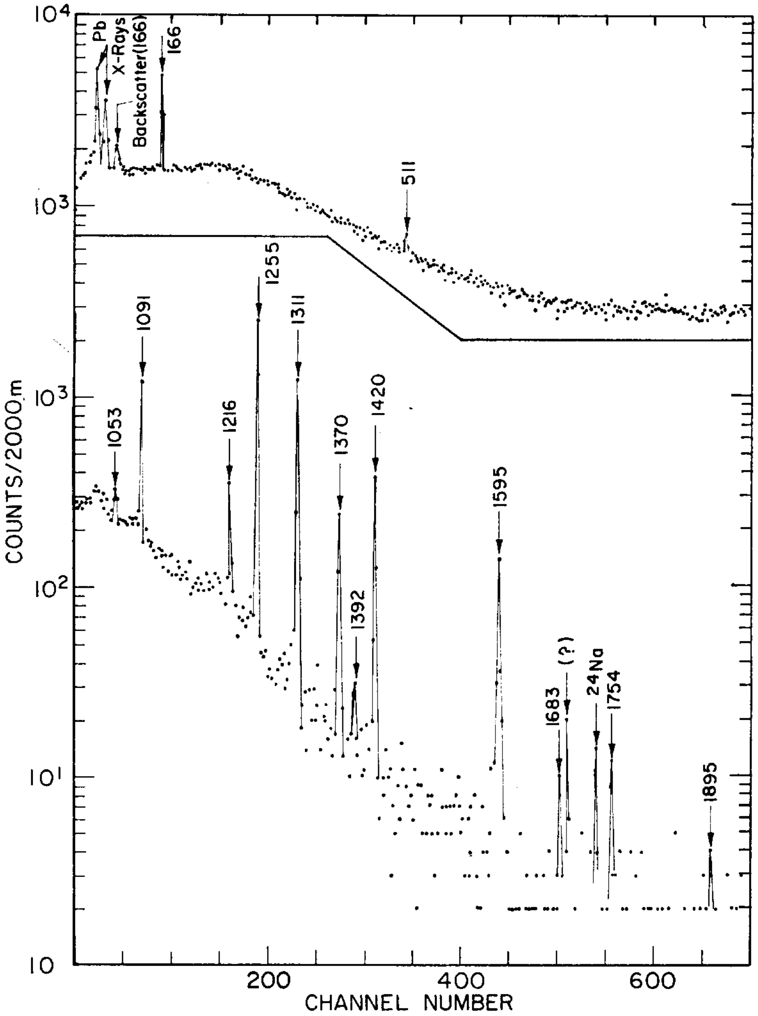

Fig. 3. The pulse-height spectrum of gamma radiation in coincidence with the 166 keV gamma ray. All energies are in keV.

strong 166 keV gamma ray in the Ge(Li) detector. The coincidence resolving time was about 85 nsec, and a true-to-chance ratio of about 5 was used. The spectrum in fig. 3 was not corrected for random coincidences. Six different sources and a total counting time of 2000 m were needed to obtain the spectrum in fig. 3.

Strong coincidences were observed with gamma rays at 1091, 1255, 1311, 1370 and 1595 keV. The peak at 1216 keV was the low-energy member of the 1217 keV doublet seen in singles spectra. Weak but definite coincidences were observed at 1053, 1392 and 1754 keV. The peak at 1732 keV was due to the impurity ^{24}Na, and the peak at about 1690 keV was due to an unidentified long-lived impurity only seen in singles and coincidence runs of longer than 800 min. The peaks at 1420 and 1683 keV were the only chance peaks seen. The peak at 166 keV is due to coincidences with Compton gamma rays from high-energy transitions that fall in the 166 keV gate. No coincidences were observed between 170 and 1050 keV. The only peak seen in this region was from annihilation radiation at 511 keV.

A search was made for coincidences with gamma rays in the region between 1000 and 2000 keV. A 40 cm^3 Ge(Li) trapezoidal detector was used The coincidence resolving time was about 90 nsec, and a true-to-chance ratio of about 2 was used. Running time was 1000 min, and a 0.32 cm Pb absorber was used to reduce the intensity of the 166 keV gamma ray in the NaI detector. A run was performed at 180° to get good statistics and at 90° to reduce the large backscatter peak In each case, the only coincident gamma ray observed besides the 166 keV gamma ray was annihilation radiation at 511 keV. The relative height of the 511 keV peak increased with time, thus indicating it to be derived from small amounts of ^{24}Na contamination.

5. Decay scheme

The gamma transition energies and intensities and their coincidence relationships have been interpreted on the basis of the decay scheme shown in fig. 4. In addition to the well-known levels at 166 and 1420 keV, 12 new levels between 1200 and 2100 keV have been established. No evidence was found for levels between 200 and 1200 keV.

The log *ft* assignments for the levels were calculated using a *Q*-value of 2380 keV obtained from beta-spectrum measurements of Mitchell *et al.* ^{1}). The relative intensity of beta transitions to the ground and first excited states was obtained from the work of Kelly *et al.* ^{3}) The internal conversion correction for the 166 keV gamma ray was made assuming it to be M1 with a 0.2 % admixture of E2 as determined by Geiger *et al.* ^{14}). The log *ft* assignments for all levels above 1200 keV were based on our intensity measurements. The *Q*-value of 2380 keV used in this work is inconsistent with the value of 2290 keV calculated by Mattauch *et al.* ^{15}). The log *ft* assignments reported here would change if our *Q*-value was incorrect, or if weak transitions were discovered between the levels above 1200 keV.

A $g_{\frac{7}{2}}$ orbital was assigned to the ground state of ^{139}La on the basis of its measured spin and magnetic dipole moment ^{16}). A $d_{\frac{5}{2}}$ orbital was assigned to the well-established 166 keV level on the basis of the M1 character of the 166 keV transition ^{14}) and the allowed character of the electron capture transition ^{16}) from the $\frac{3}{2}^+$ ground state of ^{139}Ce. The $^{139}_{56}$Ba$_{83}$ ground state is designated as ($\frac{7}{2}^-$) in analogy with the ground states of $^{141}_{58}$Ce$_{83}$ and $^{143}_{60}$Nd$_{83}$.

All gamma rays above 1000 keV were considered to populate only the ground or first excited states of ^{139}La. This placement was correct since the Q-value for beta decay was 2380 keV, and no coincidences were seen with gamma rays above 1000 keV. No evidence was found for levels between 170 and 1200 keV postulated by various experimenters $^{2,5-7}$). The 13 levels above 1200 keV were placed on the basis of precise energy and coincidence measurements. For all levels decaying to both the ground and first excited states, the energy difference between the crossover and stop-over transitions was 165.8 keV within the limits of error. In the case of levels at 1219, 1921 and 2060 keV, the energy was determined from the energy of the gamma ray containing the smallest error. Position of a level depopulated by only one gamma ray was determined by the presence or absence of that gamma ray in the coincidence spectrum shown in fig. 3. The gamma ray at 1895 keV was seen in both singles and

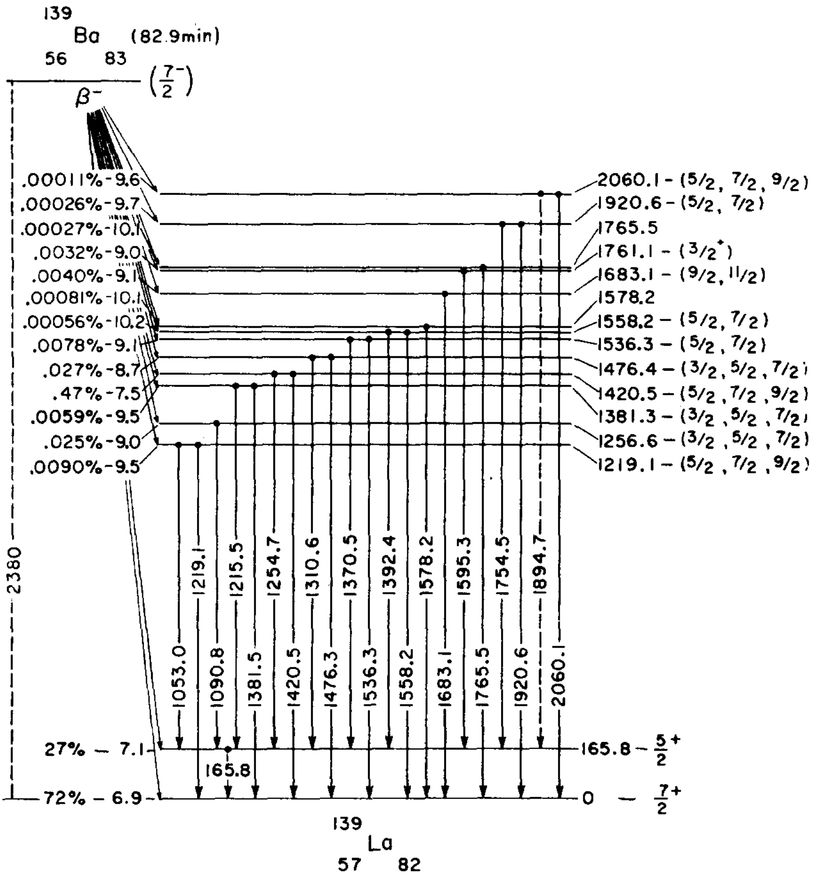

Fig. 4. The decay scheme of ^{139}Ba from the present studies.

coincidence spectra but is represented as a dashed line in the decay scheme, since its statistics were very poor and its existence in doubt.

If one assumes the ^{139}Ba ground state to be $\frac{7}{2}^-$, then the log *ft* values limit the levels in ^{139}La to $\frac{3}{2}^+$, $\frac{5}{2}^\pm$, $\frac{7}{2}^\pm$, $\frac{9}{2}^\pm$ and $\frac{11}{2}^+$. We have assigned tentative spin values to most of the levels above 1200 keV. These assignments are based on weak arguments using our measured values for log *ft* values, intensities and intensity upper limits.

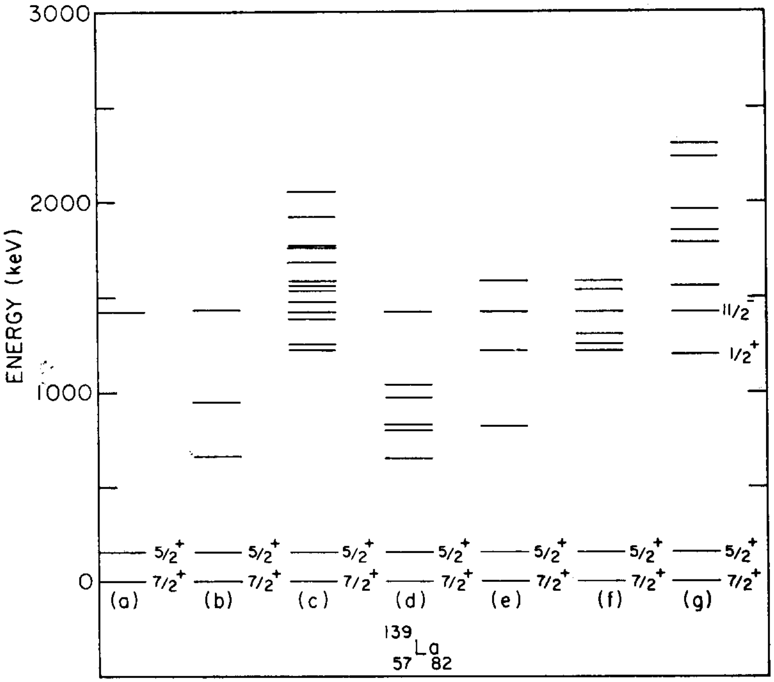

Fig. 5. Comparison of levels for ^{139}La obtained by various investigators. The experimental levels are obtained from (a) early decay studies [1,3,4]; (b) decay study of Jastrzebski [2]; (c) this work; (d) ^{139}La(^{14}N, ^{14}N′) ^{139}La reaction [6]; (e) ^{139}La(n, n′)^{139}La reaction [7]; (f) ^{139}La(n, n′) ^{139}La reaction [17]) and (g) ^{138}Ba(^{3}He, d) ^{139}La reaction [18]).

The level scheme from this work is compared with other decay scheme and reaction studies in fig. 5. Our results are consistent with the earlier work of Mitchell *et al.* [1]), Kelly *et al.* [3]) and Wasson *et al.* [4]). We find no evidence for levels at 660 and 950 keV reported by Jastrzebski [2]). Alkhazov *et al.* [6]) observed five levels between 500 and 1100 keV using inelastic scattering of 52 MeV ^{14}N ions. We did not observe any levels in this interval.

Bukarev *et al.* [7]) and Wilenzick *et al.* [17]) have observed gamma rays from inelastic neutron scattering on ^{139}La. The results of Bukarev *et al.* are consistent with ours with the exception of a level at 800 keV. Wilenzick *et al.* used Ge(Li) detectors and did not observe this level. Their results are completely consistent with ours if their gamma transition at 1310 keV is placed in cascade with the 166 keV transition as in our decay scheme. Recently, Wildenthal *et al.* 18) have observed levels in ^{139}La using the reaction ^{138}Ba(^{3}He, d)^{139}La. No levels were observed between 200 and 1200 keV. There is no close correspondence between the levels populated in the above reaction and levels populated in beta decay, but this is not surprising in view of the different mechanisms involved.

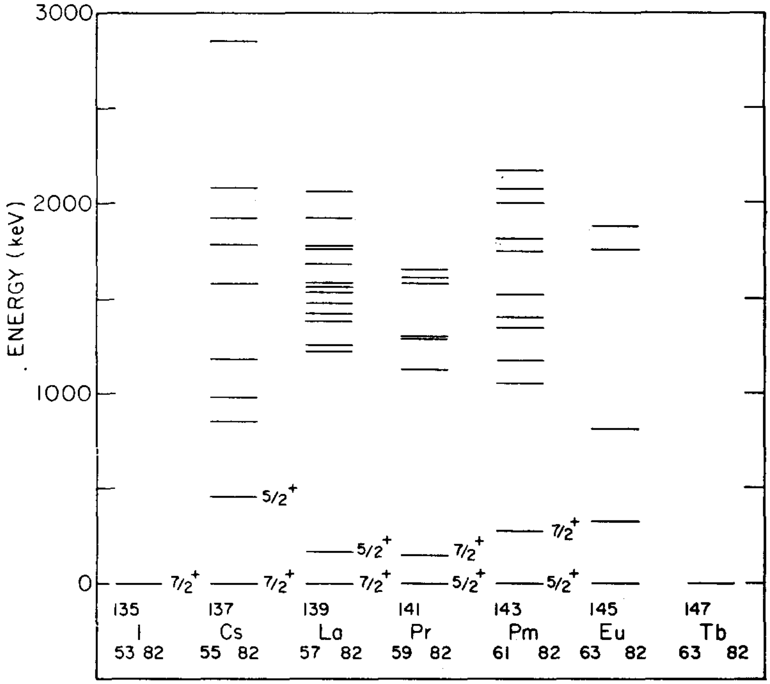

Fig. 6. Comparison of levels for various odd-mass $N = 82$ isotones.

The ground and 166 keV states of ^{139}La are thought to be the $g_{7/2}$ and $d_{5/2}$ one-quasi-particle states, respectively. The low log *ft* values are consistent with a single-particle transition from a $f_{7/2}$ neutron to a $g_{7/2}$ or $d_{5/2}$ proton. We have not observed the $s_{1/2}$ or $h_{11/2}$ one-quasi-particle states, since they would be populated through second- or third-order beta transitions respectively. Such transitions would have higher log *ft* values than found in this work. The levels at 1257 and 1761 keV are the most plausible candidates for the $d_{3/2}$ one-quasi-particle state. The relative transition probabilities to the ground and 166 keV levels are consistent with the single-proton estimates of Moszkowski 19), and the log *ft* values of 9.0 and 10.1 are consistent with those for first-forbidden unique beta transitions. The relative transition probabilities for the 1381 and 1476 keV states are inconsistent with single-proton estimates.

The log *ft* value for all states between 1200 and 2100 keV lie between 8.7 and 10.2 with the exception of the 1420 keV level.

Most beta transitions to these states are probably first forbidden, thus most of the states have positive parity.

The state at 1420 keV is of particular interest because its log *ft* of 7.5 is considerably lower than those of the other states above 1200 keV. Wildenthal *et al.*^{18}) reported a $h_{\frac{11}{2}}$ one-quasi-particle state at 1.42 MeV, but beta-selection rules eliminate this interpretation for our 1420 keV level. The low log *ft* could be explained if the level had a negative parity and was fed by an allowed beta transition. Such a state could be formed either through coupling between the $h_{\frac{11}{2}}$ one-quasi-particle state and the core or between a positive-parity one-quasi-particle state and an octupole vibration of the core. The second possibility seems the least likely since the first 3^- state ^{13}) in the neighboring $N = 82$ isotone ^{140}Ce is at 2464 keV.

A comparison of level schemes from decay work for odd-mass $N = 82$ isotones is given in fig. 6. The energy gap between the one-quasi-particle and core-excited states is evident ^{20,21}) for ^{139}La, ^{141}Pr and ^{143}Pm. The level scheme ^{22}) for ^{137}Cs does not appear to follow the general pattern, and the levels ^{23}) in ^{145}Eu are somewhat tentative. No information is available on ^{135}I and ^{147}Tb. It is interesting to note that the $g_{\frac{7}{2}}$ and $d_{\frac{5}{2}}$ one-quasi-particle states reverse order at $A = 141$. The experimental situation concerning the location of the $h_{\frac{11}{2}}$, $d_{\frac{3}{2}}$ and $s_{\frac{1}{2}}$ one-quasi-particle states is still unclear, therefore reaction data on these states have not been included in fig. 6.

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Note added in proof: Recently Wilson and Randall ^{24}) populated a level in ^{139}La at 6.12 MeV by bombardment with neutron capture gamma rays from chlorine. This level decayed to states at 1.21, 1.37, 1.41, 1.47, 1.68 and 1.76 MeV. These states may correspond to states seen in this work at 1219.2, 1381.3, 1420.5, 1476.4, 1683.1 and 1761.1 keV.

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