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# On the Decay of $^{140}$Ba to $^{140}$La [1)]

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*Abstract.* To complement results obtained by $(d, p)$ and $(n, \gamma)$ reaction spectroscopy on the structure of $^{140}$La, some details of the decay of $^{140}$Ba have been investigated using a Ge(Li) detector. Several $\gamma$-ray energies and intensities have been determined with improved accuracy. In addition, upper limits have been obtained for transitions which are important to the test of the nuclear model describing $^{140}$La.

## 1. Introduction

The structure of $^{140}$La has recently been studied in considerable detail by $(d, p)$ and $(n, \gamma)$ spectroscopy [1–4]. A simple model has been proposed [1, 2] which describes the observed properties of the lowest configuration. We need to consider only a neutron in the $|\nu f_{7/2}\rangle$ state coupled to a quasi-proton in either the $|\pi g_{7/2}\rangle$ or the $|\pi d_{5/2}\rangle$ state. Since the two-proton states are close in energy, the configurations are mixed. The state vectors describing the structure are

$$|J M\rangle_1 = \alpha_1 |\pi g_{7/2} \nu f_{7/2}; J M\rangle + \beta_1 |\pi d_{5/2} \nu f_{7/2}; J M\rangle$$

and

$$|J M\rangle_2 = \alpha_2 |\pi g_{7/2} \nu f_{7/2}; J M\rangle + \beta_2 |\pi d_{5/2} \nu f_{7/2}; J M\rangle ,$$

where the amplitudes $\alpha$ and $\beta$ are subjected to orthonormalizing conditions. According to this picture we should find 14 levels at low excitation with spins ranging from 0 to 7. All of these levels have effectively been elucidated [4]. The values of $\alpha$ and $\beta$, but not the phases have been deduced in a straightforward manner from the $(d, p)$ cross sections [1]. Since the $\gamma$-branching ratios are sensitive both to the amplitudes and to the phases of the state vectors, it is of interest to determine these ratios with the best possible precision. Some of them can be observed only in the decay of $^{140}$Ba. The results are presented in section 2.

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Within the lowest configuration, only transitions between levels whose spin difference is zero or one (M1) have been observed. Conversion studies [5] also suggest that the multipolarities are predominantly M1. Calculations using the model wave function indicate that E2 admixtures should be very small. On the other hand it is shown in Ref. [4] that the wave functions obtained from the $(d, p)$ analysis and from the fit of the branching ratios are similar but not equal. One possible explanation is that the $\gamma$-transition probabilities are more sensitive to the impurity of the wave function than the $(d, p)$ cross sections. An alternative way to test such impurity admixtures is to look for E2 components. The best evidence would be the observation of transitions between two levels whose spin difference is 2. A ground state transition from the 44 keV level, implying a spin change of 2 units, has indeed been reported [6]. We have tried to confirm this finding (section 3).

Finally, the $\beta^-$ $Q$-value is high enough to populate levels of the next configuration. In section 4 we present the results of our search for some higher energy transitions.

## 2. Experimental Method and Results

The decay of $^{140}$Ba has been investigated by several groups [5–11]. As shown in Table III, there are large discrepancies in the intensities, especially at low energies.

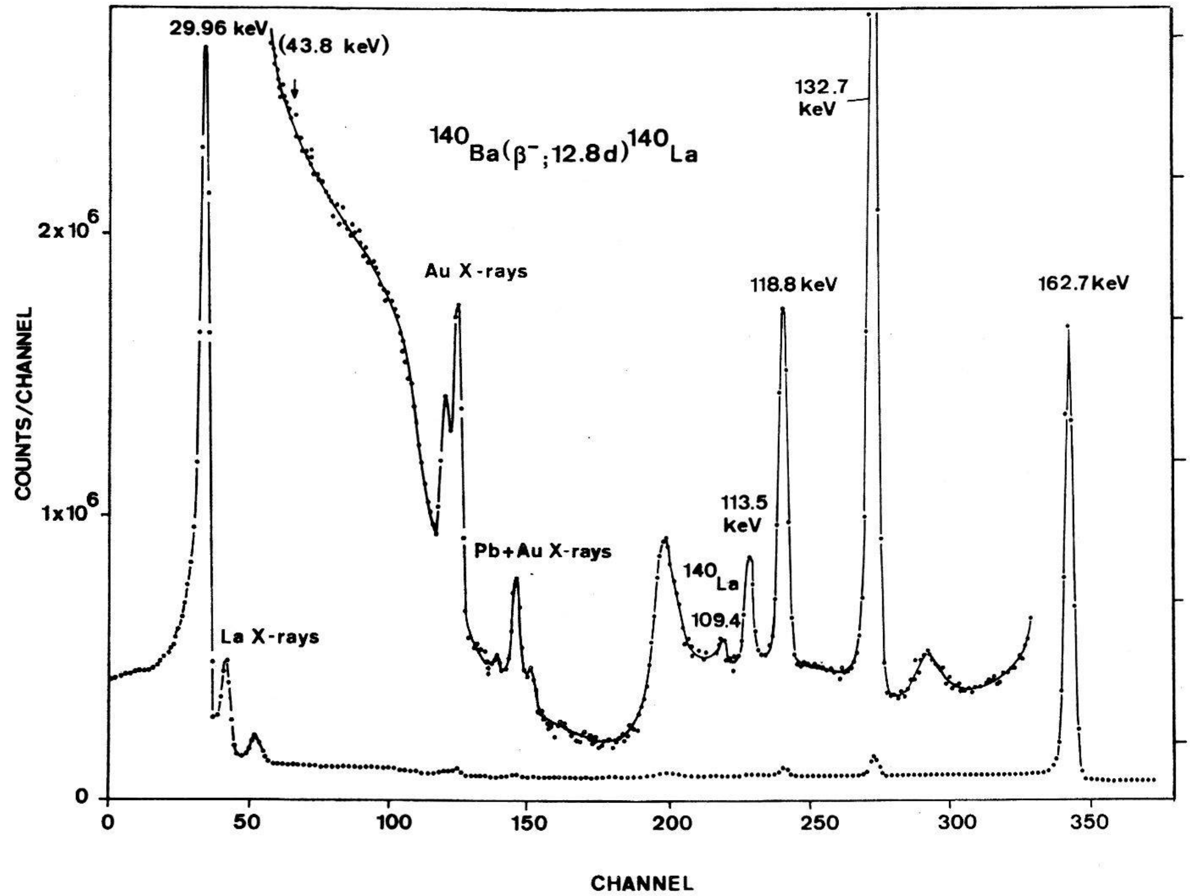


Figure 1

Low energy part of the $^{140}$Ba $\gamma$-spectrum. The left scale refers to the lower curve and the right one to the 50 times expanded upper spectrum. The solid line is only a guide for the eye. The Au and Pb $X$-rays are due to material at the surface or at the vicinity of the diode. The broad peaks to the left of the 109.4 keV and to the right of the 132.7 keV transitions are backscattering peaks.

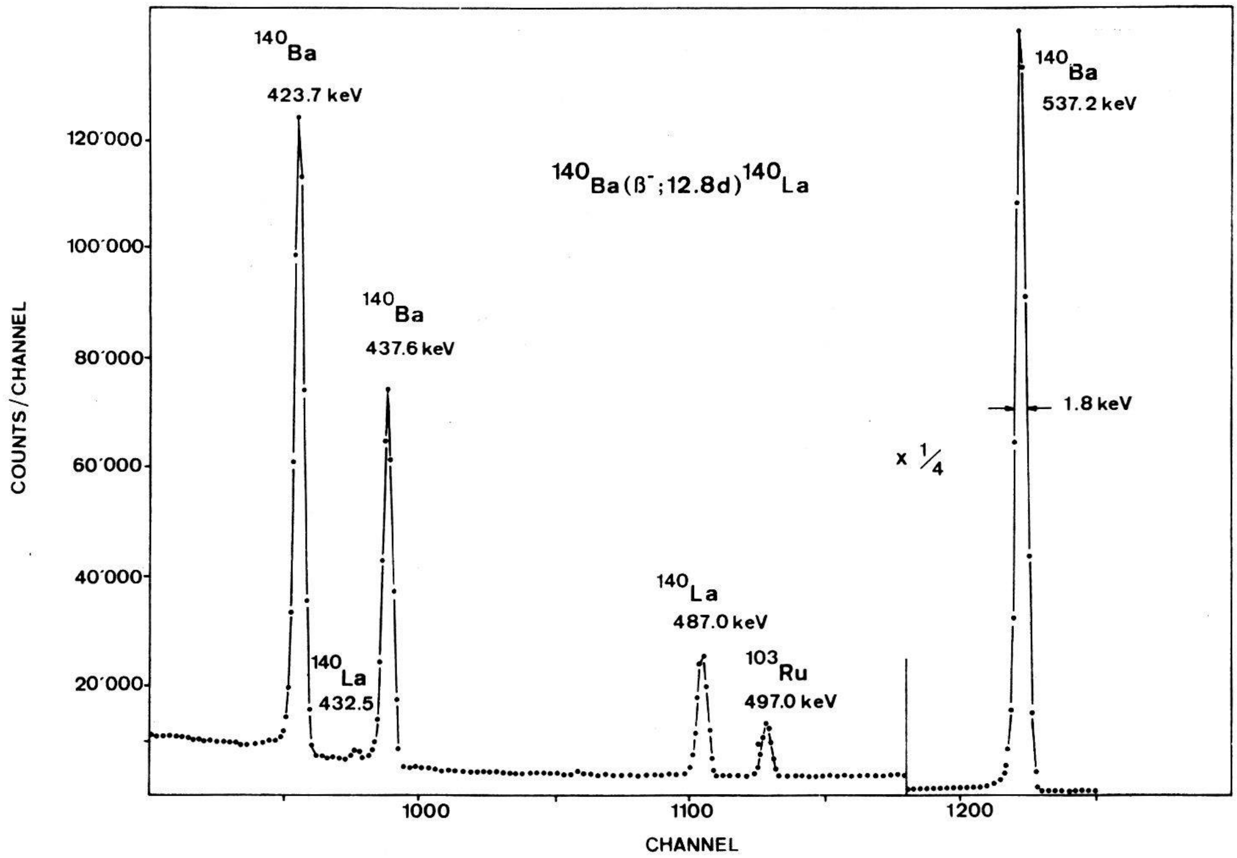


Figure 2
Intermediate energy portion of the $^{140}$Ba spectrum. The $^{140}$La activity is built during the measurement and $^{103}$Ru was present as an impurity in the source.

In our investigation we have used a Ge(Li) detector[2]) of 3 ccm coupled to a TC-202BLR amplifier and a ND-2200 4000-channel pulse-height analyser.

The resolution was 1.9 keV (FWHM) for $^{137}$Cs. Four runs of 4000 sec duration each were accumulated at an average counting rate of 4000 counts/sec. A chemical separation of the radioactive daughter nucleus $^{140}$La (precipitation of La with ammonia) was performed prior to each measurement. Figures 1 and 2 show interesting parts of the observed spectra. To judge the effectiveness of the chemical separation, we note that at equilibrium the 432.5 keV peak from the decay of $^{140}$La is nearly as high as the 423.7 keV peak. The small 432 keV residue is due to the build up of $^{140}$La during the measurements.

The energy calibration of the higher energy levels was obtained by two separate measurements of a source at equilibrium, together with primary standards ($^{192}$Ir and $^{137}$Cs). All data were analysed by a nonlinear least squares fit, the peak shapes being approximated by deformed gaussians. The details of the method have been given elsewhere [12].

A least squares fit of the transitions was made to the level energies of all 14 levels of the lower configuration, always using the most occurate energies. The adopted input values for the transitions observed in the $\beta$-decay of $^{140}$Ba are listed in Table II; the neutron capture $\gamma$-ray energies are from Ref. [4]. Only the calculated energies of the

[2]) Provided by Prof. E. Baldinger, Institute for Applied Physics, University of Basel, Switzerland.

levels observed in the $\beta$-decay are shown in Table I. The level energy differences, considered the most probable transition energies, are listed in Table II.

Table I
Level energies of $^{140}$La

| Level No. | Energy [keV] | Standard deviation [eV] |
|---|---|---|
| 0 | 0.0 | 0 |
| 1 | 29.965 | 1 |
| 2 | 43.811 | 8 |
| 3 | 162.656 | 2 |
| 4 | 467.505 | 9 |
| 5 | 581.060 | 12 |

Table II
Energies of the transitions following the $\beta$-decay of $^{140}$Ba

| This work | | Previous best value | | | Input value | | Level | Level energy diff. | |
|---|---|---|---|---|---|---|---|---|---|
| $E\gamma$ [keV] | $\Delta E\gamma$ [eV] | $E\gamma$ [keV] | $\Delta E\gamma$ [eV] | Ref. | $E\gamma$ [keV] | $\Delta E\gamma$ [eV] | init.-final | $E\gamma$ [keV] | $\Delta E\gamma$ [eV] |
| | | 13.846 | 15 | 5 | 13.846 | 15 | 2–1 | **13.846** | **15** |
| | | 29.965 | 1 | 4 | 29.965 | 1 | 1–0 | **29.965** | **1** |
| 113.560 | 30 | 113.540 | 30 | 5 | 113.550 | 30 | 5–4 | **113.555** | **20** |
| | | 118.840 | 30 | 5 | 118.840 | 30 | 3–2 | **118.845** | **15** |
| | | 132.690 | 30 | 5 | 132.690 | 30 | 3–1 | **132.691** | **3** |
| | | 162.656 | 3 | 4 | 162.656 | 3 | 3–0 | **162.656** | **3** |
| 304.840 | 20 | 304.830 | 30 | 4 | 304.840 | 20 | 4–3 | **304.845** | **15** |
| 423.695 | 30 | 423.700 | 90 | 5 | 423.695 | 30 | 4–2 | **423.695** | **20** |
| 437.550 | 30 | 437.500 | 90 | 5 | 437.550 | 30 | 4–1 | **437.540** | **15** |
| 537.250 | 20 | 537.170 | 100 | 5 | 537.250 | 20 | 5–2 | **537.250** | **20** |

To calibrate our detector efficiency, we have used $^{137}$Cs, $^{144}$Ce, $^{180m}$Hf, $^{182}$Ta and $^{198}$Au. These intensity standards were adopted after a careful compilation from the literature [13]. The measured $^{140}$La intensities are shown in Table III together with the results of previous investigations. In addition to the values obtained by direct measurement, we have computed the $\gamma$-intensities corresponding to the observed conversion electron intensities [5], using theoretical M1 internal conversion coefficients [14]. Our results are in good agreement with the latter values in the whole range and with the most recent studies [6, 11] for the high energy transitions. The results of Moss and McDaniel at low energy have a large discrepancy with all the other determinations and have not been taken into account to obtain the adopted values.

### 3. The 43.8 keV Transition

The last remarks above apply also to the search for the 43.8 keV transition. If we compare our Figure 1 with Figure 1 of Ref. [6], we note that the present data

Table III
Intensities of the transitions following the $\beta$-decay of $^{140}Ba$. When available, the errors are given beneath the values

| $\gamma$-energies [keV] | Relative $\gamma$-intensities | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Boskma [7] | Geiger Direct | Geiger $I_e/\alpha$ | Dzhelepov [8] | Agarwal [9] | Kern [11] | Moss [6] | This work | Adopted |
| 13.85 | – | | 4.6 | – | – | – | – | – | **4.6** |
| | | | 1 | | | | | | **1** |
| 29.97 | – | | 56 | 70 | 45 | – | 7.0[b] | 55 | **55** |
| | | | 10 | | | | | 8 | **8** |
| 43.8 | – | | – | – | – | – | ≤0.002[b] | <0.005 | **<0.005** |
| 113.55 | – | | 0.072 | – | – | – | – | 0.074 | **0.073** |
| | | | 0.020 | | | | | 0.008 | **0.08** |
| 118.85 | – | | 0.26 | – | – | – | 0.02[b] | 0.28 | **0.27** |
| | | | 0.06 | | | | | 0.03 | **0.03** |
| 132.69 | 5.5 | 1.1 | 0.81 | | 6 | – | 0.7 | 0.84 | **0.83** |
| | | | 0.08 | 19 | | | | 0.05 | **0.05** |
| 162.66 | 40 | 23.5[a] | 24.6[a] | | 28 | 28 | 23.2 | 25.1 | **25.0** |
| | | | | | | 3 | | 1.0 | **1.0** |
| 304.85 | 18 | 17.8 | 17.3 | 12 | 24 | 17.7 | 21.8 | 17.2 | **17.3** |
| | | 2.8 | 1.4 | | | 2.0 | | 0.7 | **0.4** |
| 423.69 | | 10.0 | 15.0 | | | 13.9 | 13.0 | 12.7 | **13.0** |
| | 18 | 2.2 | 1.3 | 18 | 19 | 1.5 | | 0.5 | **0.5** |
| 437.54 | | 9.4 | 7.2 | | | 8.8 | 7.7 | 7.8 | **7.8** |
| | | 2.2 | 0.7 | | | 1.0 | | 0.3 | **0.3** |
| 537.25 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100.0 | **100** |
| | | 16 | 8 | | | 3 | | 2 | |

[a]) Used as normalizing intensity.
[b]) This value has not been considered for the adopted value (see text).

show a distinct improvement, both statistically and in resolution. In Ref. [6] the 119 keV transition hardly appears and the 113 keV line not at all. We question the intensity limit ($\leqslant 0.002$) given for the 43.8 keV in Ref. [6].

Our failure to observe the transition is not surprising. The calculation shows that its intensity should be of the order of $10^{-5}$ to $10^{-6}$ of that of the 13.8 keV $\gamma$-ray. This is still far smaller than the limit that can now be given. It would seem more fruitful in further work to search for a 551 keV transition between the 581 and 30 keV levels. The expected intensity lies not far from our present upper limit ($< 0.03$).

## 4. Higher Energy Transitions

Reaction spectroscopy [1, 4] shows that several levels lie above 580 keV but still below the $\beta$-decay $Q$-value (1050 keV). The proton angular distribution in the $(d, p)$ reaction [1] shows that these levels belong to a configuration in which the neutron is in the $p_{3/2}$ shell. The coupling of this neutron with a quasiproton in either the $2\ d_{5/2}$ or the $1\ g_{7/2}$ state should give rise to several levels, particularly one with spin 1 and two with spin 2. The spin 1 level is not expected to be seen in the $(d, p)$ reaction, nor to be populated directly in the thermal $(n, \gamma)$ reaction. The reverse situation applies at least to one of the two $2^-$ states. The 711.7 keV level [4] which decays by the 667.6 and the 548.6 keV transitions to the lower configuration may be one of these $2^-$ states.

Considering only spin and energy differences, the 711.7 keV level and possibly one or both other levels could be fed by the $\beta$-decay of $^{140}$Ba. The log ft value of the transitions to the levels with spin 1 or 2 of the lower configuration varies between 7.7 and 9 [5]. If similar ft values would apply to the $\beta$-transitions to the upper configuration, the depopulating gamma rays should be easily observable.

From the following argument, however, we expect the situation to be not so favourable: in the $\beta$-decay to the lower configuration, the following changes take place:

$$\nu(2\ f_{7/2})^2 \to \pi(1\ g_{7/2})^1\ \nu(2\ f_{7/2})^1\ ,$$

whereas to the upper configuration we must have

$$\nu(2\ f_{7/2})^2 \to \pi(1\ g_{7/2})^1\ \nu(2\ p_{3/2})^1\ .$$

The first transition involves the change of one particle only, but the second requires the change of two particles; the latter is therefore certainly retarded compared to the first.

In Figure 3 the higher energy part of the spectrum is shown. We have not found evidence for any new transition. A transition with a log ft value of 9 would give rise to $\gamma$-rays with an intensity comparable to the 574 keV line in Figure 3. We therefore conclude that $\beta$-transitions to the upper configuration have log ft values larger than 10.


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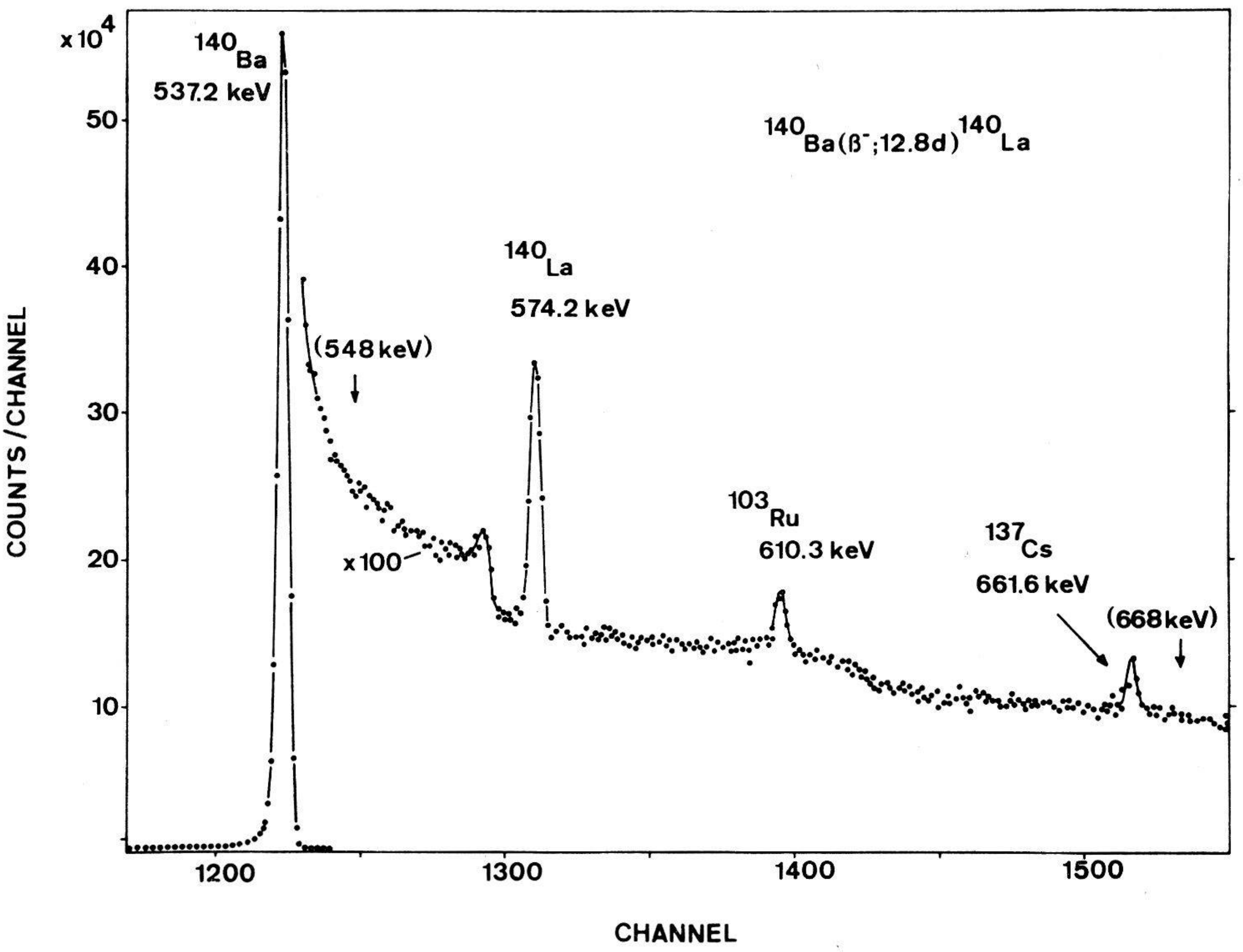


Figure 3
High energy portion of the $^{140}$Ba $\gamma$-spectrum. $^{103}$Ru and $^{137}$Cs were present as impurities in the source. The small peak left of the 574 keV line (double escape peak) is due to pile-up.

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