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FIRST DIRECT OBSERVATION OF STRONG INTERACTION SPIN-ORBIT EFFECTS IN ANTIPROTONIC ATOMS*)

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ABSTRACT

The strong $\bar{p}$-nucleus spin-orbit interaction was investigated in a measurement of the strong-interaction effects of the 9 → 8 transition in $\bar{p}^{174}$Yb at the Low-Energy Antiproton Ring (LEAR) at CERN.

This measurement was part of an experimental programme where, for the first time, the fine-structure components of the last observable X-ray transition in a $\bar{p}$ atom, which carries information on the strong $\bar{p}$-nucleus interaction, were resolved and studied individually. The observed splitting $\Delta E_{exp} = 2408 \pm 26$ eV consists of the electromagnetic fine-structure splitting $\Delta E_{FS} = 2350$ eV and an additional splitting $\Delta\epsilon = 58 \pm 26$ eV . In addition, one finds a significant difference in the level widths of $\Delta\Gamma = 195 \pm 59$ eV with the larger value $\Gamma_{\downarrow\downarrow} = 1216 \pm 41$ eV for the lower fine-structure level.

This experiment follows an earlier measurement on $\bar{p}^{138}$Ba, where the transition 8 → 7 is influenced by the strong interaction. In this case, however, the fine-structure components could not be resolved.

The results for ^{174}Yb may be attributed to a spin-orbit (LS) term in the complex strong-interaction potential.

1. INTRODUCTION

In the investigation of the strong $N\bar{N}$ interaction great progress has been made, in particular for $\bar{p}$ atoms, since the start-up of the Low-Energy Antiproton Ring (LEAR) at CERN.

Its intense pure $\bar{p}$ beam allows the collection of high-statistics data. Thus one has the possibility of studying weak transitions in an energy region up to now 'forbidden' owing to low detector efficiency.

Measurements of strong-interaction effects in light $\bar{p}$ atoms have already been published [1, 2]. The goal was to establish a general scaling behaviour of the strong interaction and to provide experimental data for comparing it with existing potential models. In this context also isotope effects were measured in order to investigate particular details of the strong interaction potential [3] and the E2 resonance effect was applied to get access to hidden levels [4].

It was pointed out some time ago [5], that the spin–orbit term of the $\bar{p}$–nucleus interaction can be investigated directly by measuring the strong-interaction shift and width in atomic fine-structure levels separately. Here we report on the first observation of different shifts and widths in the lowest observable levels. Preliminary results were already presented in an earlier paper [6, 7]. The information was obtained from the resolved fine-structure components of the 'last observable transition' 9 → 8 in the measured $\bar{p}$ X-ray spectrum of the heavy nucleus ^{174}Yb. In the following we present the final results.

2. THE $\bar{p}$-ATOMIC ENERGY LEVELS IN THE STRONG-INTERACTION REGION

In the region where the strong $\bar{p}$–nucleus interaction becomes important, the equation of motion for the $\bar{p}$–nucleus system is usually extended by a complex potential U(r), accounting for the strong interaction.

This potential can schematically be constructed by folding the nucleon distribution of a nucleus with the elementary complex $\bar{p}N$ potential u(r). It is

$$U(r) = \int \varrho(r') \times u(|\vec{r} - \vec{r}\,'|)\, d^3r' \quad , \tag{1}$$

where the real part of u(r) is derived, in general, from the known NN potentials, transformed for the $N\bar{N}$ case. It contains a central potential u_C, a spin–orbit term u_{LS}, the tensor term u_t, and a spin–spin contribution u_σ. The imaginary part, introduced phenomenologically, normally consists of a central potential only, since up to now there has been no need for further terms.

The solution of the extended Dirac equation leads to complex eigenvalues

$$E^* = E^{em} + \epsilon + i\Gamma \quad , \tag{2}$$

where ϵ and Γ describe the energy-level shift and broadening, caused by the strong interaction.

The investigation of the spin–orbit potential of the $\bar{p}$–nucleus interaction is governed by the following aspects:

i) Since we are principally interested here in the effect of the LS potential, a selected nucleus should have zero spin (no hyperfine structure) and no tensor force (even–even nucleus), so that $U(r) = U_C(r) + U_{LS}(r)$ only.

ii) Except in the case of the E2 nuclear resonance, in a $\bar{p}$ X-ray spectrum only the last observable transition and thus the corresponding energy levels n_i and $n_f = n_i - 1$ influenced by U(r) are in general accessible to strong-interaction-effect measurements; only from this transition can one therefore derive information on the strong $\bar{p}$–nucleus interaction, since all transitions to $n < n_f$ are too weak to be observed.

iii) For an undisturbed atomic energy level the electromagnetic fine-structure splitting is

$$\Delta E_{FS} \propto [Z\alpha]^4/[n^3\ell(\ell + 1)] \quad . \tag{3}$$

The intensity ratio for the allowed E1 transitions between two levels $|n, \ell, j = \ell \pm ½\rangle$ and $|n' = n - 1, \ell' = \ell - 1, j' = \ell' \pm ½\rangle$, denoted by a, b, and c in Fig. 1, is

$$I_a : I_b : I_c = j[2j + 3] : 1 : [j(2j + 1) - 1] \quad . \tag{4}$$

The dominance of a and c with increasing total angular momentum j reduces in practice the given line triplet to a line doublet for high n (see definition of j in Fig. 1).

iv) By measuring the fine-structure splitting of the last observable transition in a $\bar{p}$ X-ray spectrum,we can extract information about possible differences in the contribution of U(r) in the individual fine-structure components and thus separate the effect of $U_C(r)$ and $U_{LS}(r)$.

In order to reach high precision in the measurement of LS effects, the electromagnetic splitting of the fine-structure components a and c has to be larger than the detector resolution. This can be achieved with a nucleus of high Z owing to the Z dependence of ΔE_{FS} shown in Eq. (3).

After a search for an appropriate nucleus and a first measurement on ^{138}Ba, we selected the even–even nucleus ^{174}Yb. Its last observable transition $\bar{p}^{174}$Yb 9 → 8 at $E_{theor} = 402$ keV fulfils the above-mentioned conditions; the electromagnetic splitting $\Delta E_{theor}(a - c) = 2350$ eV [8] is precisely known.

Although the fine-structure components of the 8 → 7 line could not be resolved in $\bar{p}^{138}$Ba, the average shift and width could be determined. The spectrum of $\bar{p}^{138}$Ba, measured with one detector only, is shown in Fig. 2 for the region of the 8 → 7 transition.

3. THE APPARATUS

The experiment has been carried out with four high-purity germanium semiconductor detectors, placed around a thin metal-plate target.

Incoming antiprotons were identified by a scintillator telescope. They were slowed down in a wedge-shaped polyethylene degrader in order to stop in the target. The resulting characteristic $\bar{p}$ X-rays were detected with the Ge diodes, covering an energy range up to 1290 keV.

A detailed description of the experimental set-up, including the detector electronics and the data-acquisition system, can be found elsewhere [2, 6, 9].

The data were taken at an initial $\bar{p}$ momentum of 300 MeV/c. The ytterbium target was a round metallic plate of 3 cm diameter and ≈ 300 mg/cm^2 thickness. The barium target was a compressed $Ba(NO_3)$ powder in a square frame of 3 cm × 3 cm and also of 300 mg/cm^2 thickness. The number of stopped antiprotons was 3,866 million for the Yb and 1,198 million for the Ba.

4. DATA ANALYSIS

The spectra from the four Ge detectors have been evaluated. In three cases the fine-structure components of the transition 9 → 8 could be clearly resolved. Figure 3 shows the fitted region in the spectrum of detector D6 (1134 mm^2 area, 12.5 mm thickness).

4.1 The calibration

The detectors were calibrated off-line with standard sources of ^{75}Se, ^{133}Ba, and ^{241}Am. In beam the undisturbed $\bar{p}^{174}$Yb X-ray transitions were used to calibrate the spectrum. For three of the detectors, a linear polynomial was sufficient for the energy calibration; in one case, a 3-parameter polynomial gave the best fit.

The detector resolution as a function of energy was fitted as follows:

$$R = b_0 + b_1\sqrt{E} \quad . \tag{5}$$

The contribution of the calibration error to the total experimental error was small (2 eV), since for the relative measurement the low-energy component a of a resolved line doublet serves as reference line.

4.2 The fit of the $\bar{p}^{174}$Yb 9 → 8 transition

For all detectors the fitted region around the interesting transition was chosen to be identical and the same peak pattern was fitted with a linear background. The fit of the last observable transition in ^{174}Yb was based on the following assumptions:

i) Owing to the weakness of the b component (3‰ of the total intensity), it is sufficient to include only the two circular transition components a and c in the fit. Furthermore parallel transitions do not play any role, since their contribution was calculated to be < 4‰ of the total intensity.

ii) The peak positions can be fitted independently, since the fine-structure components are clearly resolved.

iii) The instrumental Gauss widths of the two fine-structure components are calculated from the width of an undisturbed X-ray transition and the off-beam resolution function (5) by adjusting b_0 for the in-beam resolution. Their values are kept as fixed numbers in the fit.

iv) The intensity ratios I_a/I_c for the last observable transition and higher $\Delta n = 1$ transitions are given by the statistical population, under two conditions:

A) The relative difference between the strong interaction effects on the two states of the upper level $n = 9$ is small (< 1%).

B) No possible disturbing effect (e.g. the E2 resonance effect) influences the main fine-structure components a and c of any $\bar{p}$ X-ray transition in a different way. Since both conditions are fulfilled, one can write

$$I_a/I_c = (h_a/h_c) \times (\ell_a/\ell_c) = \text{const.} \quad , \tag{6}$$

where h and ℓ are the peak height and Lorentz width of a line component, respectively.

A χ^2 analysis of the ratios h_a/h_c and ℓ_a/ℓ_c, keeping at the same time the product I_a/I_c constant, led in all detectors to a minimum of the χ^2 of the fits for the same ratio ℓ_a/ℓ_c (= 0.86). The values given for the shifts and widths in Yb are calculated for this ratio.

5. RESULTS

The results of the data evaluation are summarized in Table 1. The shifts and widths for the two components of the fine-structure doublet (a,c) are given separately.

The total experimental error for the ^{174}Yb measurement contains, besides the statistical uncertainty:

i) in the case of the splitting: A) the error due to the contribution of unknown weak background lines (7 eV), B) the calibration error (2 eV), and C) the error due to the choice of the fitted region (5 eV),

ii) in the case of the determination of the line-width difference: A) the deviation from the statistical population distribution (2 eV) in the $n = 9$ level, B) the error in the determination of the instrumental Gauss widths (2 eV), and C) the error due to weak background lines (20 eV). This last value is based on the assumption that, in the worst case, such a line hits only one of the components.

Separately for each detector, these errors have been added quadratically to the statistical error.

The resolution of our detectors at the transition energy of 402 keV was about 1.2 keV. The errors of the ^{138}Ba measurement are mainly due to statistics.

The effects observed in the transitions are identified with the displacement and broadening of the 8j level (^{174}Yb) and the 7i level (^{138}Ba), respectively. The subscript a denotes $j = \ell + \frac{1}{2}$ and c denotes $j = \ell - \frac{1}{2}$ for the total angular momentum quantum number. For comparison also the electromagnetic fine-structure splitting ΔE_{theor} is given in Table 1.

While in our ^{138}Ba measurement the differences are within the errors, in ^{174}Yb the shift and width in the lower fine-structure level ($j = \ell - \frac{1}{2}$) in the 8j state are clearly larger. The two main results of this experiment are

$$\Delta\epsilon = \epsilon_{\ell+1/2} - \epsilon_{\ell-1/2} = 58 \pm 26\,\text{eV} \tag{7}$$

and

$$\Delta\Gamma = \Gamma_{\ell+1/2} - \Gamma_{\ell-1/2} = -195 \pm 59\,\text{eV} \tag{8}$$

for the 8j level in ^{174}Yb.

The effect on the width is about three times as big (in absolute values) as in the shift, a ratio which is characteristic of strong-interaction effects in $\bar{p}$ atoms [10]. The difference amounts to about 18% of the average strong-interaction effect and is hence relatively large. The difference in the shift is about 2.5% of the electromagnetic fine-structure splitting.

It should be noted that the shifts in ^{174}Yb are positive (attractive), which means that the strong interaction increases the binding of the level. This is an unusual result for $\bar{p}$ atoms. It is in agreement with an earlier, less precise measurement by Roberson et al. [11], where, however, the fine-structure components could not be resolved.

6. DISCUSSION

6.1 Average shifts and widths

The strong-interaction effects in ^{138}Ba have been measured for the first time. For ^{174}Yb there exists a previous measurement [11], which is in agreement with our results. However, our new measurement improved the precision by about one order of magnitude. Theoretical calculations were done on the basis of a black-sphere model by Kaufmann and Pilkuhn [12], in the framework of a relativistic impulse approximation by Sparrow [13] with a $\bar{p}$–nucleus potential calculated from the Paris potential by Wicht and von Geramb [14] and with one based on the Dover–Richard model presented in Refs. [15, 16]. All results are summarized in Table 2.

The widths are well reproduced by the theoretical calculation of Kaufmann and Pilkuhn, by that of Sparrow, and still by that of Heiselberg, whilst Wicht and von Geramb arrive at too low a value. The average shift in ^{174}Yb is not reproduced by any calculation: all the given values are negative.

6.2 Differences in shifts and widths of the fine-structure levels

Possible differences in strong-interaction effects in two fine-structure levels were calculated theoretically in various approaches. In the first calculation of this kind, Nishimura and Fujita [17] extended the local optical potential by a gradient term, whose strength they derived from a one-boson-exchange model. Unfortunately, they performed the calculations of the level shifts and widths only for light nuclei, where the fine-structure pattern cannot be resolved. Depending on the density distribution and the strength of the local potential, they obtain differences in the shift which range from 5% to 100% of the average shift.

Suzuki and Narumi [18] recently constructed a more elaborate p̄-nucleus potential which also includes a gradient term. They calculated the spin-orbit effect for ^{16}O only and obtained an up to 17% difference in width and up to 40% difference in shift, with the larger shift in the lower total angular momentum state.

Dumbrajs et al. [16], who constructed a p̄-nucleus potential from the Dover-Richard model, did a systematic analysis of the contribution of the central, the tensor, and the spin-orbit term to the strong-interaction effects in light nuclei. They found that in the 3d levels of ^{16}O the shifts differ by 18% and the widths by 5%.

Sparrow [13], Wicht [14] and Heiselberg [15] calculated the shifts and widths for the 8j levels in ^{174}Yb. These are compared with our results in Table 3. While Sparrow's calculated difference in width is only 1.3 standard deviations away from our result, the theoretical value of Wicht and von Geramb does not agree with our measurement. Also the Aarhus group [15] finds a difference too small for the width. All theoretical calculations are unable to reproduce the observed difference in shift. They find a larger repulsive shift in the lower fine-structure level. It is amazing, however, that the absolute value of their differences in shift is compatible with our result.

Only Wicht and von Geramb [14] have given information on the contribution of the different overlap of the final-state (here 8j) electromagnetic wave functions with the nucleus (electromagnetic LS effect) and an LS-dependent term (Thomas term) in the p̄-nucleus potential. They found that the electromagnetic effect amounts to 19 eV in the shift difference and to 120 eV in the width difference. It would be interesting to compare that to other calculations.

Clearly, more theoretical studies are needed to reproduce the observed effect. Also the recent observation of an abnormal intensity ratio of the last observable transition in ^{148}Nd [19] may provide additional information.

7. SUMMARY

We have measured for the first time the strong-interaction shifts and widths separately in the two fine-structure components of an atomic level and found a significant difference. Theoretical models only partially reproduce the observed strong-interaction effects. In particular, they obtained shifts which differ even in sign from our results. The theoretical model based on the relativistic impulse approximation approach comes closest to the measured data. The observed difference in shift and width in the two fine-structure levels can at least partially be attributed to a spin-orbit-dependent term in the $N\bar{N}$ potential.

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Table 1

Line shifts and widths in the $\bar{p}^{174}$Yb 8j and $\bar{p}^{138}$Ba 7i levels

Electromagnetic transition energies and fine-structure splitting (in keV)					
Transition	E_{theor}	ΔE_{theor}			
$\bar{p}^{174}$Yb 9 → 8	402	2.350			
$\bar{p}^{138}$Ba 8→7	375	2.094			
Shifts ϵ (in eV)					
Nucleus	Level	$\langle\epsilon\rangle$	ϵ_a	ϵ_c	$\Delta\epsilon$
^{174}Yb	8j	312 ± 39	283 ± 36	341 ± 43	58 ± 26
^{138}Ba	7i	−306 ± 101	−257 ± 101	−356 ± 101	−99 ± 143
Level width Γ (in eV)					
Nucleus	Level	$\langle\Gamma\rangle$	Γ_a	Γ_c	$\Delta\Gamma$
^{174}Yb	8j	1118 ± 41	1021 ± 41	1216 ± 41	195 ± 59
^{138}Ba	7i	1864 ± 522	1725 ± 455	2161 ± 664	436 ± 805

Table 2

Theoretical and experimental results
for the strong-interaction effects in ^{138}Ba and ^{174}Yb (in eV)

^{138}Ba		^{174}Yb		Ref.
$\langle\epsilon_{7i}\rangle$	$\langle\Gamma_{7i}\rangle$	$\langle\epsilon_{8j}\rangle$	$\langle\Gamma_{8j}\rangle$	
−306 ± 101	1864 ± 522	312 ± 39	1118 ± 41	This experiment
-	-	260 ± 460	1480 ± 660	[11]
-	1060	-	1131	[12]
-	-	− 96	1132	[13]
-	-	−140	817	[14]
−235	1965	− 71	1010	[15]

Table 3

Theoretical and experimental results
for the strong-interaction effects in the separated 8j level of ^{174}Yb (in eV)

^{174}Yb						Ref.
Shifts ϵ_{8j}			Widths Γ_{8j}			
ϵ_a	ϵ_c	$\Delta\epsilon$	Γ_a	Γ_c	$\Delta\Gamma$	
283 ± 36	341 ± 43	58 ± 26	1021 ± 41	1216 ± 41	195 ± 59	This exp.
− 60	− 131	− 71	1072	1191	119	[13]
− 120	− 160	− 40	780	862	82	[14]
− 63	− 79	− 16	996	1024	28	[15]

Figure captions

Fig. 1 Level scheme showing the 9 → 8 transition in $\bar{p}^{174}$Yb.

Fig. 2 Spectrum of the 8 → 7 transition in $\bar{p}^{138}$Ba.

Fig. 3 Spectrum of the 9 → 8 transition in $\bar{p}^{174}$Yb.

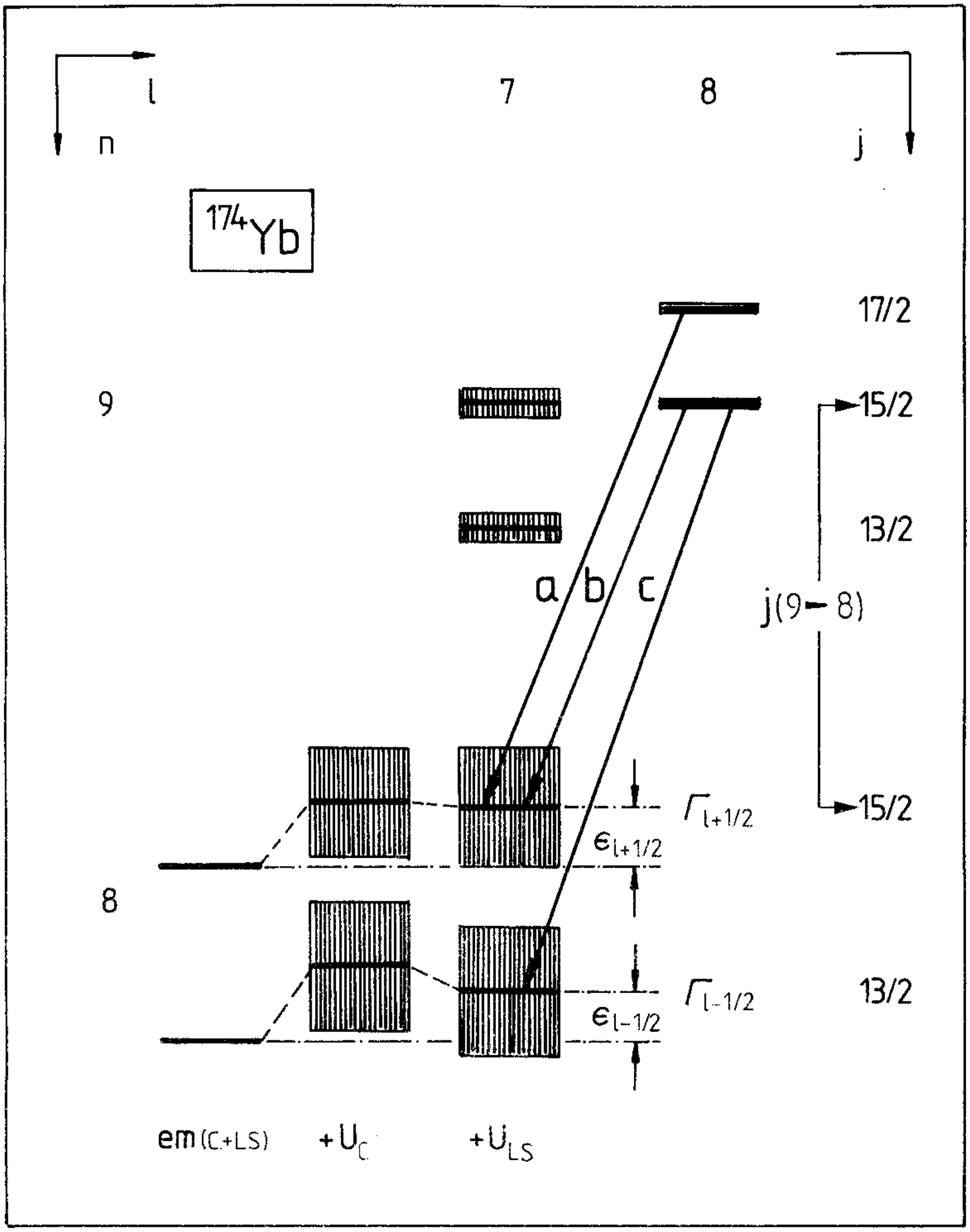
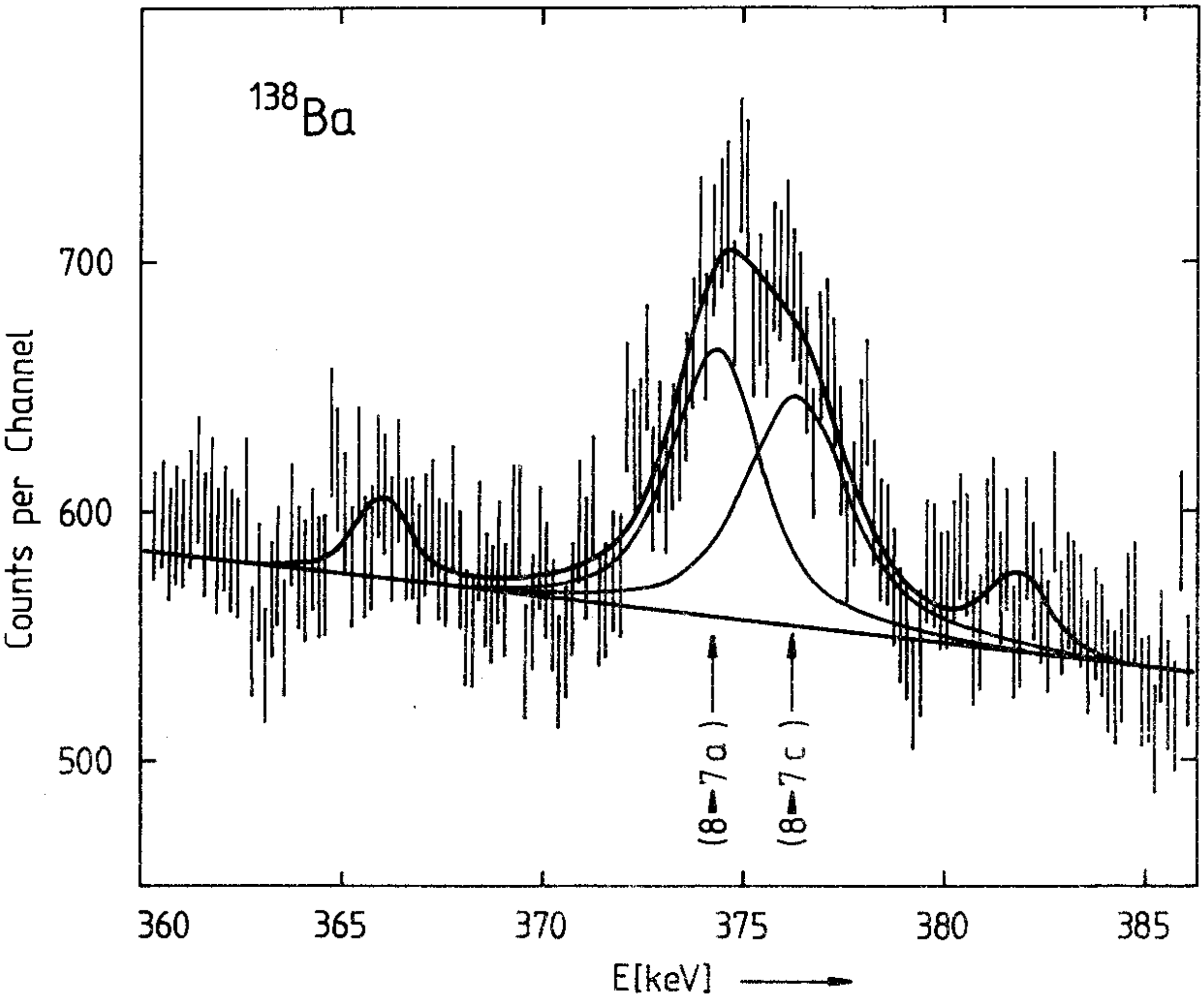

l
7
8
n
j
^{174}Yb
17/2
9
15/2
13/2
a
b
c
j(9→8)
15/2
$\Gamma_{l+1/2}$
$\epsilon_{l+1/2}$
8
13/2
$\Gamma_{l-1/2}$
$\epsilon_{l-1/2}$
em (C+LS)
+U$_C$
+U$_{LS}$

Fig. 1



^{138}Ba
Counts per Channel
700
600
500
(8→7a)
(8→7c)
360
365
370
375
380
385
E[keV]

Fig. 2

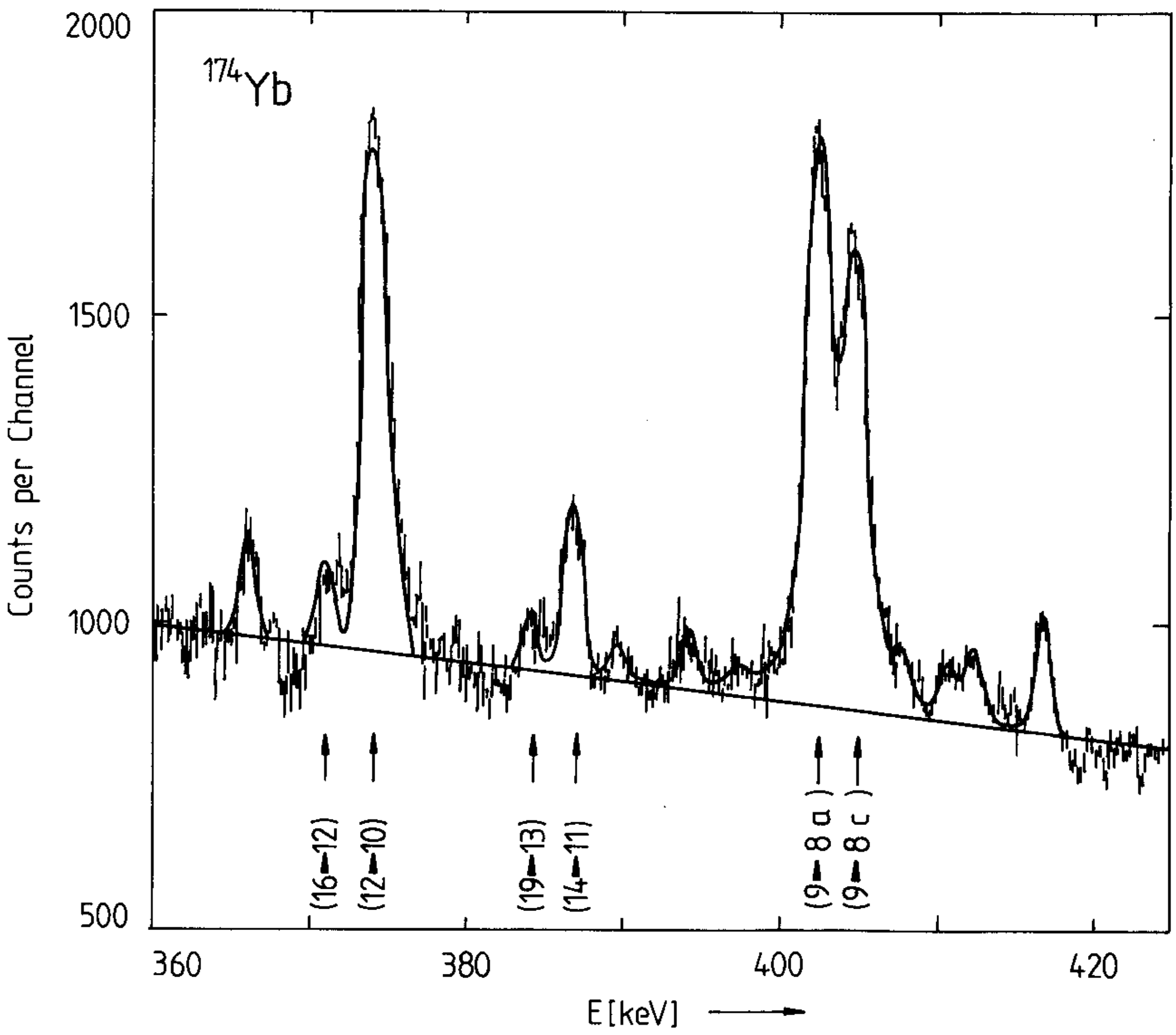

2000
1500
1000
500
Counts per Channel
^{174}Yb
(16→12)
(12→10)
(19→13)
(14→11)
(9→8 a)
(9→8 c)
360
380
400
420
E[keV] ⟶

Fig. 3