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RESULTS OF THE SEARCH FOR K-SERIES X-RAYS FROM KAONIC HYDROGEN

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ABSTRACT

The X-ray spectrum associated with K^- stopping in liquid hydrogen was measured with high resolution Si(Li) detectors. The total K X-ray yield is not larger than 8×10^{-4} per stopped K^-. A weak line pattern was found, which was tentatively ascribed to the K^-H K-series X-rays. The shift and width of the 1s level, deduced from this pattern, are $\varepsilon_{1s} = +270 \pm 80$ eV and $\Gamma = 560 \pm 260$ eV, respectively.

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1. INTRODUCTION

The precise measurement of X-ray spectra of kaonic atoms reveals a shift, broadening, and intensity reduction of lines caused by the strong interaction of the orbiting kaon with the nucleus. The theoretical interpretation of the data obtained in this way needs knowledge of the kaon-nucleus interaction near but below threshold [1-3]. This interaction has been studied by K-matrix analysis of K^-p and K^+p scattering data below 300 MeV/c [4]. However, the Y_0^* renders the determination of the K^-N interaction parameters from the low-energy scattering data alone quite difficult. Thus the measurement of the K^-N scattering lengths by the study of kaonic hydrogen and deuterium is very important.

The experiments on kaonic hydrogen are especially difficult as compared to other kaonic atoms because targets of liquid hydrogen have to be used in order to stop a sufficient number of kaons. The high density in turn leads to collision-induced absorption due to Stark effect. According to cascade calculations [5,6] the $2p \to 1s$ X-ray yield per captured kaon should be of the order of 10^{-3}. These calculations are based on assumptions about the K^-p scattering length and about unknown parameters (such as, for example, the velocity of the kaonic atoms in liquid hydrogen), neither of which are well known.

The phase-shift analysis of Martin resulted in a K^-p scattering length [3,4] of $a_{K^-p} = -0.66 + i0.70$ fm. This scattering length would lead to a repulsive shift of the 1s level in K^-H of $\varepsilon_{1s} = -270$ eV and to a width of $\Gamma = 580$ eV.

Recently a group at the Rutherford Laboratory [7] has reported the observation of the 2p-1s transition from kaonic hydrogen. The intensity was $(1.1 \pm 0.6) \times$ $\times\ 10^{-3}$ per stopped kaon and the energy was 6.52 ± 0.06 keV. This corresponds to a shift of $\varepsilon = (+40 \pm 60)$ eV. The line width was compatible with the experimental resolution, which was 230 eV FWHM. The line showed up most clearly in that part of the spectrum which was delayed by as much as 60 ns with respect to the prompt part. Such timing delays for soft X-rays were so far never observed [8].

2. EXPERIMENTAL SET-UP

Details of our experimental set-up can be found in a publication [9] describing the $\bar{p}p$ experiment; here we give only a brief summary.

The experiment was done at the k_{19} low-momentum electrostatically separated beam of the CERN Proton Synchrotron (PS). The kaons were slowed down in a moderator, and about 65% of the remaining kaons were stopped in the liquid-hydrogen target ($\emptyset$ = 12 cm, length = 16 cm $\hat{=}$ 1.13 g/cm^2). Five Si(Li) detectors, each of 80 mm^2 active area and 350 eV energy resolution at 5 keV, were used to detect the X-rays. The geometry of the target and of the detector is shown in Figs. 1 and 2 of Ref. 9. The energy and the time of the X-ray event were recorded event by event on magnetic tape via a PDP-11 computer. Typical stopping rate per burst was 400 K^-.

3. DATA-HANDLING AND RESULTS

The off-line analysis described in Ref. 9 showed that the accidental background was only about 1% of the continuous prompt background. The timed prompt spectrum as shown in Fig. 1 is smoothed in order to help the eye to find structures hidden in the statistical fluctuations. In Figs. 2 and 3 the statistically correct, i.e. unsmoothed, spectrum is shown together with the fit of peaks and background. The spectrum was obtained with 9×10^7 K^- stopped in the target.

There are several distinct lines at energies above 10 keV, but they originate from X-rays of K^- and secondary negative pions stopping in the mylar vessel, the super-insulation around the target, and the Al housing of the diodes. Three weak lines can be attributed to Σ^-C X-rays, the yield of these transitions relative to the K^-C lines being about four times larger than that calculated by Zieminska [10], assuming that the Σ^- are produced in C. However, the K^- interacting with hydrogen produce Σ^- more efficiently than with heavier nuclei, part of which may reach the target walls and thus form Σ^-C atoms.

In Table 1 the energies and intensities of these lines are given together with their identification.

A detailed analysis of the spectrum reveals the existence of a few very weak lines in the energy region below 10 keV. Two fitting procedures were used. One procedure used variable parameters, except for the peak width which was set equal to the detector resolution. The results are presented in Table 1 and Figs. 2 and 3. The other method used a pattern of three peaks locked in position relative to each other (pattern fit I in Table 2). The position differences used in the pattern were the calculated electromagnetic values of the 2p, 3p and 4p levels. It was also possible to fit the pattern with a Lorentzian width, yielding a value of $\Gamma_L = 0.56 \pm 0.26$ keV (pattern fit II in Table 2).

The statistical significance of these lines (the K^-p K-series candidates) is about 2 and 3 standard deviations for each of them. The probability of obtaining such a line pattern is 5×10^{-3}, as estimated with a special Monte Carlo test.

A similar pattern has been seen in the $\bar{p}H$ spectrum [9]. There it was discussed whether it could be attributed to the K_α lines of Fe, Cu, and Zn. In the present K^-H spectrum, however, the K_α line of Fe at 6.40 keV is not visible, though Fe should be the most abundant impurity atom (Ref. 9). This makes the above-mentioned hypothesis less likely. This absence of electronic X-rays in the K^-H spectrum could, irrespective of their possible presence in the $\bar{p}H$ spectrum, be explained by the fact that the number of secondary particles and γ-rays per stopped K^- is smaller than in the $\bar{p}H$ case. This fact is manifested by a lower continuous background per incoming stopped particle in the K^-p measurement.

4. DISCUSSIONS AND CONCLUSION

We see a line pattern which corresponds to the expected transitions in the K-series of the K^-p system. It is very unlikely that this could have been generated by statistical fluctuations. For line widths smaller than the experimental resolution, the upper limit for the K-series yield is $\sum_n Y_{np-1s} \leq 8 \times 10^{-4}$ per stopped kaon in liquid hydrogen, while for a single transition in the K-series, $Y \leq 4 \times 10^{-4}$ with a confidence of 95%. If the line pattern originates from the K-series transitions then there is a shift of $\varepsilon_{1s} = +0.27 \pm 0.08$ keV, a value which has the opposite sign compared with the value expected from analyses of scattering data [4]. The width $\Gamma_L(1s) = 0.56 \pm 0.26$ keV has a large error due to the variations of the relative positions in the free fit compared with the pattern fit (see Table 2). This Γ_L is, however, not in conflict with predictions [4].

Our experimental yield is in agreement with theoretical calculations performed by Borie and Leon [6] but is in disagreement with the experimental value of Davies et al. [7]. They reported a yield of $(1.1 \pm 0.6) \times 10^{-3}$ for a transition with an energy of 6.52 ± 0.06 keV. For this energy an upper limit of the yield $Y < 3 \times 10^{-4}$ can be obtained from our experiment. From the difference in transition energy as well as from the fact that the line of Ref. 7 shows up essentially in the delayed spectrum, the conclusion can be drawn that the origins of the peaks are not the same.

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Table 1

Energies and intensities of all lines fitted in the energy region from 5 keV to 33 keV. The half-widths of the lines were fixed to the detector resolution.

Transition	Energy (keV) [a]	Area ± fit error	Remarks
K^-C			
4 → 3	22.05 ± 0.03	276 ± 32	
5 → 3	32.32 ± 0	74 ± 30	
5 → 4	10.22 ± 0	138 ± 34	A small admixture of K^-Al 8 → 7
K^-O			
5 → 4	18.34 ± 0.03 [b]	125 ± 31 [b]	Same energy as π^-C 3 → 2
6 → 4	28.26 ± 0.13	49 ± 25	
6 → 5	9.82 ± 0.10	72 ± 31	E_{th} = 9.97 keV
K^-Al			
6 → 5	26.65 ± 0.03	248 ± 30	
7 → 6	16.09 ± 0	59 ± 29	
Σ^-C			
5 → 4	23.44 ± 0.09	69 ± 27	
6 → 5	12.72 ± 0.11	58 ± 28	
7 → 5	20.06 ± 0.11	57 ± 27	
π^-C			
3 → 2	18.34 ± 0.03 [b]	125 ± 31 [b)c)]	Same energy as K^-O 5 → 4
4 → 2	24.83 ± 0	26 ± 7 [c]	
π^-O			
3 → 2	32.84 ± 0	20 ± 31	
π^-Al			
4 → 3	30.42 ± 0.02	495 ± 36 [d]	
5 → 4	14.04	< 80	
6 → 4	21.7 ± 0	34 ± 3 [d]	

(cont.)

Table 1 (cont.)

Transition	Energy (keV) a)	Area ± fit error	Remarks
Not identified	5.10 ± 0.09	78 ± 35	
	6.27 ± 0.12	56 ± 33	
	6.96 ± 0.09	78 ± 34	K^-p candidate 2 → 1
	7.99 ± 0.07	102 ± 34	" " 3 → 1
	8.64 ± 0.10	64 ± 33	" " 4 → 1
	10.99 ± 0.07	99 ± 30	
	17.46 ± 0.07	83 ± 28	
	19.11 ± 0.08	80 ± 28	
	20.74 ± 0.14	52 ± 28	Due to asymmetric line profile
	21.29 ± 0.15	48 ± 28	" " " " "
	25.36 ± 0.13	48 ± 26	πN 3 → 2 25.10 keV e)
	29.60 ± 0.18	34 ± 26	
	31.33 ± 0.25	24 ± 28	

a) Zero error means locked to calculated energy.

b) The area is split equally between the two peaks.

c,d) The relative intensities are locked to each other.

e) From boron nitride, which is a constituent of the Si(Li) detector.

Table 2

Energies and intensities of the X-ray line pattern tentatively ascribed to the K-series of K^-p. The width of the lines was fixed at the value of the detector resolution. The calculated electromagnetic energies are 6.46, 7.66, 8.08, and 8.61 keV for the $2 \rightarrow 1$, $3 \rightarrow 1$, $4 \rightarrow 1$, and $\infty \rightarrow 1$ K-series transitions, respectively.

	Energy (keV)	Events in peak	Yield (per stopped K^-)
Free fit	(Position and intensities are free; resolution is locked)		
	6.96 ± 0.09	78 ± 34	2.1×10^{-4}
	7.99 ± 0.07	102 ± 34	2.5×10^{-4}
	8.64 ± 0.10	64 ± 33	1.5×10^{-4}
Pattern fit I	(Intensities are free; resolution and rel. positions are locked)		
	6.83 ± 0.07	64 ± 33	
	8.02	89 ± 33	
	8.45	36 ± 33	
Pattern fit II	(Intensities and Γ_L are free; resolution and rel. positions are locked)		
	6.86 ± 0.08	180 ± 104	
	8.04	122 ± 95	
	8.48	194 ± 118	
	Γ_L = 0.56 ± 0.26		

Figure captions

Fig. 1 : The prompt X-ray spectrum of the K^-p measurement. The spectrum is treated by a smoothing procedure.

Fig. 2 : The low-energy region of the prompt spectrum together with the fit of peaks and a third-order background.

Fig. 3 : The high-energy region of the prompt spectrum together with the fit of peaks and a third-order background.

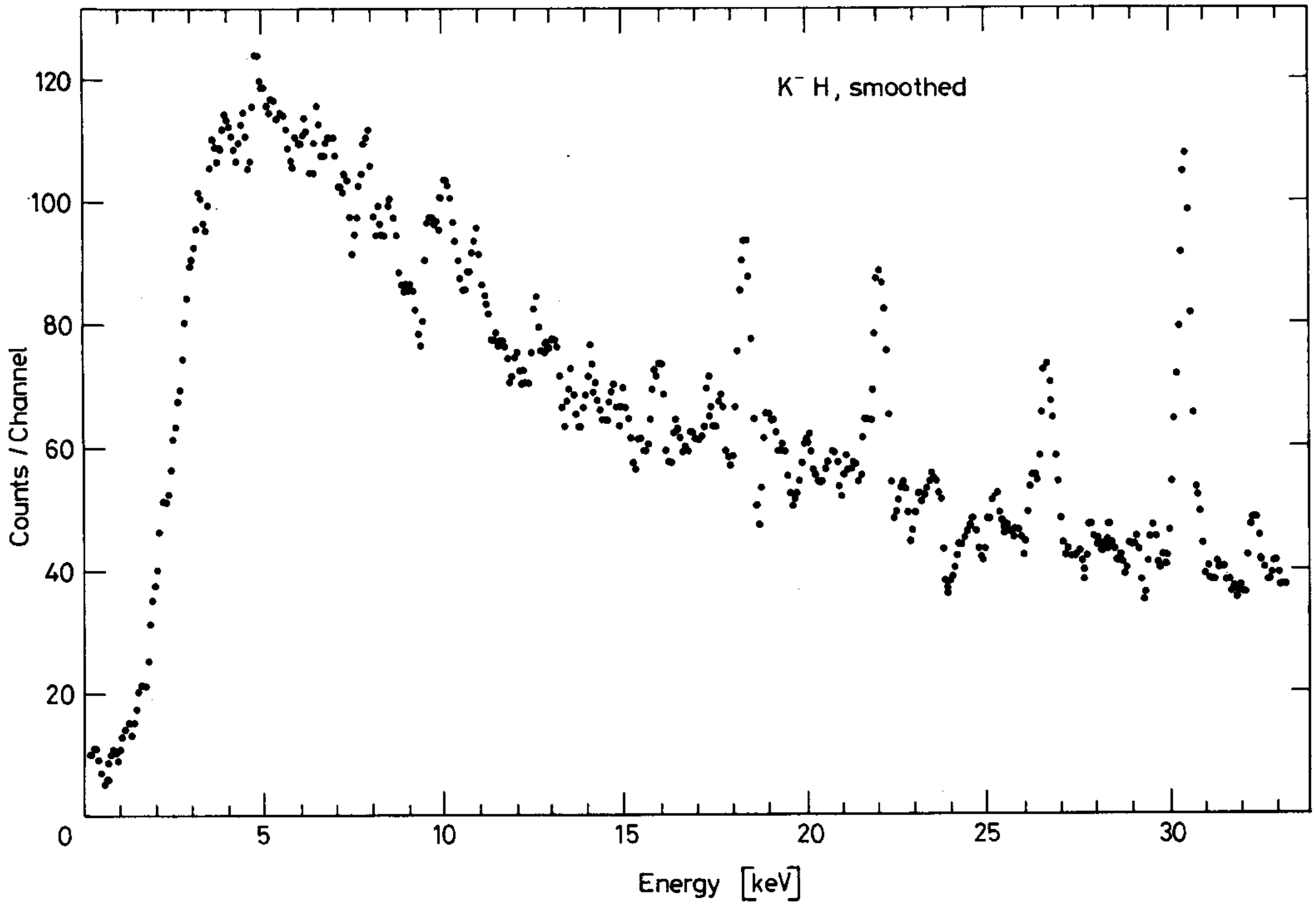
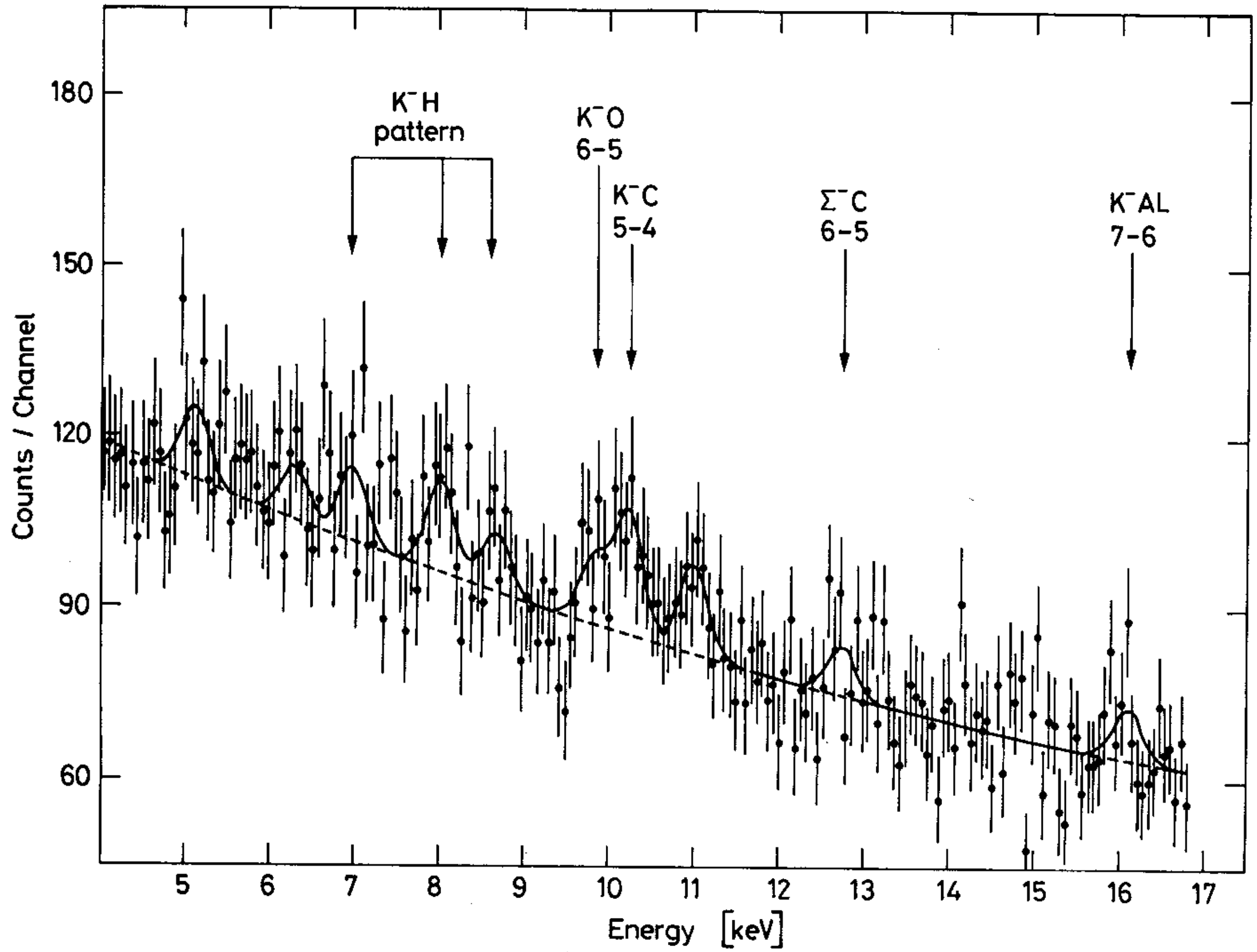

K⁻ H, smoothed
Counts / Channel
120
100
80
60
40
20
0
5
10
15
20
25
30
Energy [keV]

Fig. 1



180
150
120
90
60
Counts / Channel
K⁻H
pattern
K⁻O
6-5
K⁻C
5-4
Σ⁻C
6-5
K⁻AL
7-6
5
6
7
8
9
10
11
12
13
14
15
16
17
Energy [keV]

Fig. 2

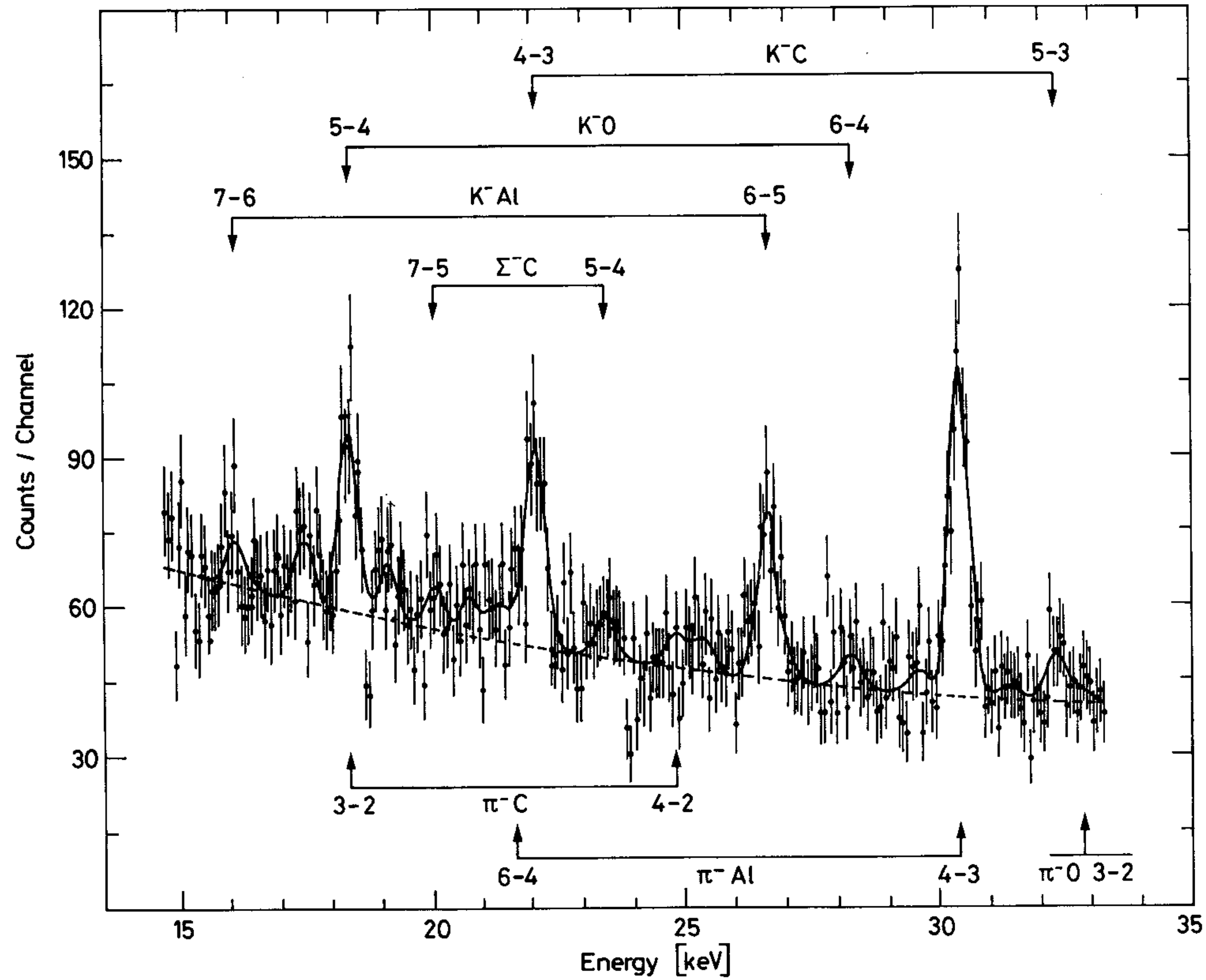

4-3
K⁻C
5-3
5-4
K⁻O
6-4
7-6
K⁻Al
6-5
7-5
Σ⁻C
5-4
3-2
π⁻C
4-2
6-4
π⁻ Al
4-3
π⁻O 3-2
150
120
90
60
30
Counts / Channel
15
20
25
30
35
Energy [keV]

Fig. 3